DEVELOPMENT OF A LOW COST H - DARRIEUS ROTOR BLADE FOR A SMALL VERTICAL AXIS WIND TURBINE

HAROUB AHMED HAROUB

MASTER OF SCIENCE

(Energy Technology)

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Development of a Low Cost H - Darrieus Rotor Blade for A Small Vertical Axis Wind Turbine

Haroub Ahmed Haroub

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University

Signature ………………………………................ Date………………………….

Haroub Ahmed Haroub

This thesis has been submitted for examination with our approval as University Supervisors.

Signature  Date 13th September, 2016

Mr. Francis Xavier Ochieng'

IEET - JKUAT, Kenya

Signature ………………………………............. Date………………………….

Dr. Joseph N. Kamau

JKUAT, Kenya

DEDICATION

This work is dedicated to my dear parents; My Dad Ahmed Sheikh Harub and my Mum Lula Abdirahman. Thank you for your love and support.

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LIST OF ABBREVIATIONS

ASALS	Arid and Semi-Arid Lands
AFPM	direct drive Axial Flux Permanent Magnet
ESO	Epoxidased soya oil
FiT	Feed-in Tariff
GRP	Glass reinforced plastic
HAWT	Horizontal axis wind turbine
MW	Mega Watt
NACOSTI	National Commission for Science Technology and Innovation.
PLA	Polylactic acid
PV	Photovoltaic
RPM	Revolution per minute
SMEs	Small and medium micro enterprises
VAWT	Vertical axis wind turbine

LIST OF NOMENCLATURE

A	Turbine rotor area (m^2)
B, b	Number of blades
C, C	Chord length (m)
D	Drag force (N)
d	Rotor diameter (m)
G	Interference factor
H	Rotor height (m)
L	Lift force (N)
P	Output power (W)
R, r	Rotor radius (m)
S	Blade area (m^2)
T	Torque (NM)
U	Wind blade velocity (m/s)
V	Absolute wind velocity at the rotor blade (m/s)
W	Relative wind velocity (m/sec)
C_p	Rotor power coefficient
C_t	Thrust coefficient
C_n	Normal force coefficient
C_l	Coefficient of lift force
C_d	Coefficient of drag force
P_a	Available power (W)
P_w	Power extracted by rotor (W)
P_{max}	Maximum power (W)

T_a	Thrust (N)
Re	Reynolds number
X	Tip Speed Ratio

Greek letters

σ	Solidity
θ	Angle attack of the wind (Degree)
α	Blade pitch angle (Degree)
ρ	Density of the air (kg/m^3)
ω	Angular velocity of the rotor (rad/s)
γ	The blade position (Degree)
Ω	Angular velocity of the experimental models (rad/s)

ABSTRACT

Due to the context of high-energy expenditure in rural areas, Small Wind Turbines are an appropriate solution capable of inducing much needed development opportunity in Kenya's rural areas. However, utilization of wind energy faces challenges due to the high cost of the imported wind turbines, poor manufacture and/or inefficient locally made wind turbines and lack of appropriate skills base in manufacture. Development of efficient low-cost wind turbines coupled with a strong strategy stands to be a major determinant to promote commercialization on these technologies. This study fabricated three vertical axis rotor blades that aimed to generate power under relatively low wind speed velocities. Using an open source Qblade wind turbine design software a model was developed. The model optimized chosen design parameters to come up with a prototype of the rotor blade. A final prototype design sizing was a rotor diameter of 2m and length of 1.6 m with a chord length of 0.2 m. and A NACA 0021 airfoil. The selection of the airfoil was influenced by its thickness (21% of chord) and its self-starting behaviour. Based on the final prototype design a full-scale turbine was constructed for experimental validation. The material used was Glass fibre reinforced plastics (GFRP). Blade production process involved making of the master blade used to form the mould that was used to make the blade copies. The blade copies were taken through a sequence stages of lamination, drying, trimming, and smoothing. The power coefficient of the turbine was tested using a wind fan by subjecting it to wind speeds ranging from 4 m/s to 15 m/s. The maximum power coefficient was 0.1 and occurred at TSR of 4. A battery was used to provide the load in the experiment and controlled by an inverter. A direct drive Axial Flux Permanent Magnet (AFPM) generator developed for small scale vertical axis wind turbine (VAWT) was coupled to the turbine rotors to determine the electricity generation capacity. A speed of 14 m/s gave the highest power of 190 W at 280 RPM, 12 m/s gave the highest power as 156 W at 230 RPM, 10 m/s gave the highest power as 120W at 180 RPM while 8 m/s gave the highest power as 96 W at 140 RPM. 280 was the rated RPM for the Generator. The turbine torque was 1.5Nm at an RPM of 175. The turbine has high torque but low rotational speed and a high gear ratio generator may achieve higher power output.

Alternatively, multipole electrical generators can be used for direct coupling with the wind rotor. The cost of production of the Rotor blade with all components was about Ksh. 120,000. This cost included buying of the shaft, hubs and bearing (Ksh. 25,000) and the blades amounted to about Ksh. 21,000. In comparison a HAWT turbine of same sizing costs between KSH 100,000-200,000. As Most local suppliers do not supply VAWT, a comparison with the international price of VAWT of same sizing was about Ksh 180,000. The cost benefit analysis of the system considering an annual energy yield 245 Kwh and the system cost of Ksh 130,000 had electricity generation costs of USD 0.2 per KWh.

CHAPTER ONE

INTRODUCTION

1.1 Background to Study

Wind energy has been used in Kenya for many years primarily for lifting water in remote ranches and mission outposts. It was one of the earliest forms of energy to be introduced into the country at the turn of the 20th century. In early 1990s a grant by the Belgium government introduced three 200 kW wind electric turbines into the country to run a grid fed two turbine system rated at 350kW while the third 200 kW turbine was hybridized with a diesel power plant to feed the remote town of Marsabit in the north of the country (SWERA, 2008). Ngong wind farm currently has a power output of 25.5 megawatts. There are a total of 30 turbines in operation each producing 850 KW (Kengen, 2015). Undergoing development is the Lake Turkana wind power project that involves development and construction of a 300 MW wind farm. The project is located at a remote location, approximately 12 kilometres east of Lake Turkana in north-western Kenya. The wind farm will comprise 365 wind turbines of a capacity of 850 KW each. In addition to the Wind Turbine Generators (WTGs) and their foundations, a 33 KV electrical collector network will be constructed. (KEREA, 2014).

Some topography specificities (channelling and hill effects due to the presence of the Rift Valley and various mountain and highland areas) have endowed Kenya with some excellent wind regime areas. The North West of the country (Marsabit and Turkana counties) and the edges of the Rift Valley are the two large windiest areas (average wind speeds above 9m/s at 50 m height) (KEREA, 2014). The coast is also a place of interest though the wind resource is expected to be lower (about 5-7 m/s at 50 m height) (KEREA, 2014). Many other local mountain spots offer good wind conditions. Due to the monsoon influence, some seasonal variations on wind resource are expected (low winds between May and August in Southern Kenya). Kenya’s wind resource is determined from wind speed data from meteorological stations. There are 55 wind masts and data loggers that have been installed to collect site specific data country wide (SWERA, 2014)

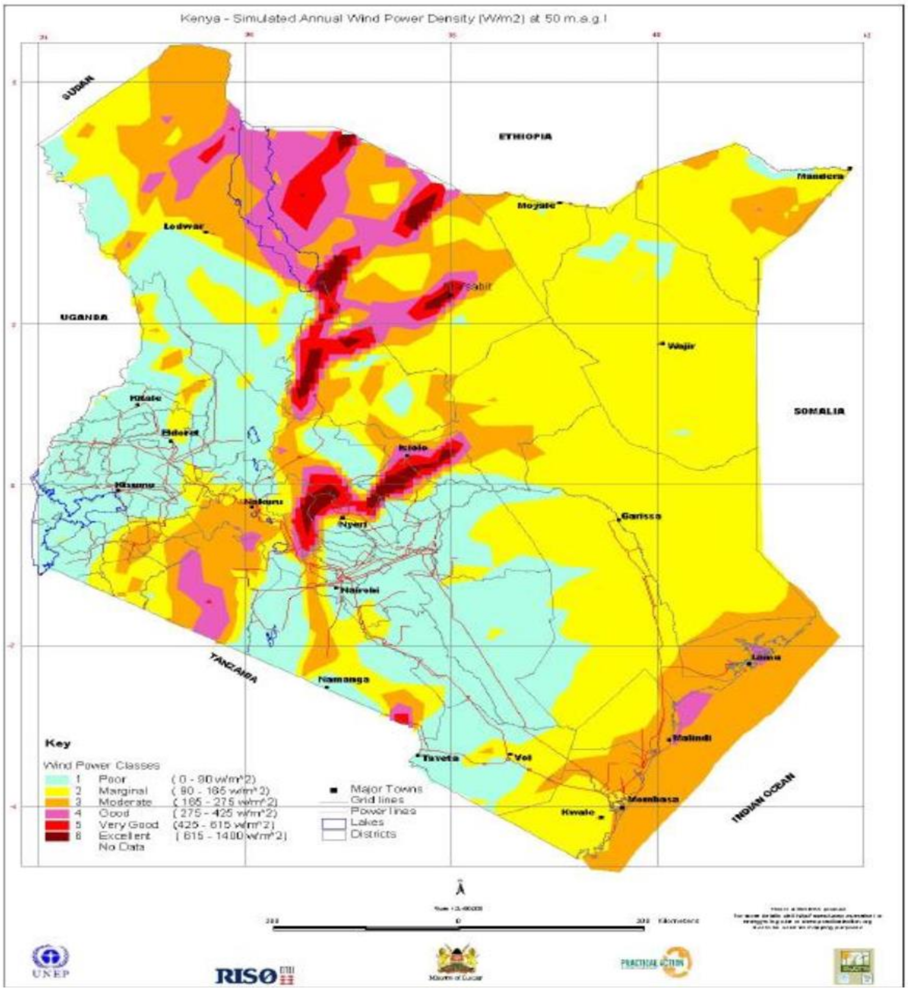


Figure 1.1: Wind Resource Distribution in Kenya (SWERA, 2008)

The Kenya national energy policy objective is to ensure adequate secure, affordable, sustainable and reliable supply of energy to meet national and county development needs, while protecting and conserving the environment. The policy also aims to prioritize and promote the development of local technologies in energy development and delivery. However, this aspect is yet to be fully realized and some of the hindering factors include low adoption of renewable energy technologies despite the huge potential the country has. The low adoption is accelerated by the high cost of imported turbines. The Feed-in Tariff (FiT) Policy provides a fixed tariff not exceeding Ksh 12 per Kilowatt-hour for wind generated electricity. The tariff applies to individual wind power plants (wind farms) whose effective generation capacity is above 500kW and does not exceed 100 MW. As a result of the publication of the FiT, there has been a lot of interest among potential investors to exploit the resource. The Government has given approval to 20 applications with a combined proposed capacity of 1,008 MW and a further 300 MW under negotiated terms. The proposed projects are at various stages of implementation. (KEREA, 2014).

According to Global Tracking Framework report (World Bank, 2014) under the Sustainable Energy for All Initiative to measure levels of energy, development of market for locally manufactured small energy technologies was noted to be one of the indicators to attain energy security and exploitation of renewable energy sources. The Government of Kenya Wind Resource Assessment report (Windforce, 2013) shows an average wind speeds of 4 - 5 m/s could provide excellent opportunity for enhancing access to modern energy sources in rural areas using renewable energy sources. However, the cost of acquisition is proving to be inhibiting as demonstrated by the slow uptake of the technology given the massive potential the country holds. The current price for a 0.4 KW wind turbine made of cast aluminium and carbon fibre is between Ksh 76,000 and Ksh 110,000 and 1 KW costs Ksh 450,000.

An average of 80-100 small wind turbines (400 W) have been installed to date, often as part of a Photovoltaic (PV)-Wind hybrid system with battery storage. Most of these wind turbines are imported although a few Kenyan companies have recently started locally manufacturing wind turbines ranging from 150 W – 6 KW and have installed 50 turbines to date. Wind pumps are more common than wind turbines, 2 local companies manufacture and install wind pumps. Installations are in the range of 300-350 KW (SWERA, 2014).

Currently, there exist small scale pico-wind turbine manufacturers, though efficiency is noted to be pretty low, these systems have not really penetrated the market (IEET Small Wind workshop proceedings, 2013). The existence of these manufacturers is rarely known by potential users in addition the pricing of these turbines is no clear and consistent.

To facilitate uptake of these technologies, development of efficient low-cost wind turbines stands to be a major determinant coupled with a strong strategy to promote commercialization on these technologies. This research aimed to design and fabricate a low cost prototype wind rotor blade of an H- Darius rotor to be used as a vertical axis wind turbine under low wind speed conditions. The project has a commercialization strategy for promoting the uptake of locally manufactured small wind turbines, the designs targets low income population and used simple and locally available materials for easy manufacturing in small workshops by people with basic technical skills such as Jua Kali artisan.

1.2 Statement of the Problem

The global human population is steadily increasing, putting more pressure on the energy sources that are available. Furthermore, looking at our country, the increasing population means more people need more energy, and since the country is also ambitious in industrialising, then more and more energy is required.

The cost of installing electricity is still out of the reach of many Kenyans as approximately 85 per cent of Kenyans living in rural areas cannot afford electricity due to high the costs of connection. The traditional centralised infrastructure is not sustainable to meet the needs of the vast population; the best investment is utilising available resources like wind energy. Wind is available in most parts of Kenya throughout the year, with research statistics indicating a mean wind speed of 4 m/s in Arid and Semi-Arid Lands (ASALs).

1.3 Justification of the Study

Kenya is amongst the countries with the highest energy prices, which are a hindrance to the development and sustainability of small and medium micro enterprises (SMEs). The country’s total energy mix is 1,708 megawatts, with hydro making up half or 808 megawatts. Diesel-fired plants, which account for a third of Kenya's power basket or 542 megawatts, deliver energy at a cost of between Sh22.60 and Sh31.30 (US cents 26-36), pushing up the price of power (Business daily, 2015). The SMEs play a greater role in alleviating poverty in the country. With most of Kenya's population leaving below the poverty line, this trend of eradicating poverty will always remain a pipe dream. The poor need energy that is not only affordable but also environmentally sustainable.

The potential savings with wind turbines for home use can be particularly substantial. With optimal conditions home owners could see an 80% to 90% decrease in energy costs, but this is dependent upon consistent wind on the property. Utilizing a wind turbine is a green option that many home owners can greatly benefit from making it an attractive decision not only for energy conservation but for substantial potential savings on energy costs. Feed in Tariffs (FiTs) in Kenya have tended to attract mainly big investors dealing with big wind turbines (above 500 KW per turbine) e.g. the Ngong wind park and the Lake Turkana Wind project. They have also tended to support wind projects for electricity generation that is fed into the grid.

The Arid and Semi-Arid areas in Kenya consist of mostly nomads in search of water and pasture for their cattle. There are places which will not have electricity access, these places coincide with the poorest and isolated rural areas of developing countries, and these people cannot afford the cost of a wind turbine, nor small nor bigger. Imported wind turbines on the other hand are also very expensive to buy and maintain. A small wind turbine design that can be built with simple workshop materials and tools would make a difference in their living conditions. The product of this research a turbine capable of producing power for small wind regimes with small household usage in offgrid areas like the ASAL can bring a positive change in their power needs. The design targets the low income population and uses simple and locally available materials in order hence affordable. VAWTs have a constant shape along their length allowing for an easier design, fabrication and replication of the blade resulting in cost reduction. H- Darrieus Rotor blade are also simple and cheap to construct, can accept wind from any direction eliminating the need for reorientation, has high starting torque at low operating speed.

1.4 Hypothesis

i. Locally manufactured rotor blades are cheaper than the imported blades.
ii. The locally manufactured H-Darrieus rotor blades are simpler to construct and easier to maintain.

1.5 Objectives

1.5.1 Main objective

The main objective of this research was to design and develop and fabricate a suitable low cost H- Darrieus VAWT rotor blade that can operate well even for low wind speed sites.

1.5.2 Specific objective

The specific objectives of the study were:

1. To design, model and fabricate a low cost H-Darrieus rotor using locally available materials.

2. To carry out economic analysis of producing a low cost darrieus wind rotor in Kenya

3. To test the performance of a low cost darrieus rotor blade.

1.6 Scope of study

The scope of this thesis is to design and build a vertical axis wind turbine rotor blade that is capable of producing power. The design of the turbine will include modelling of a vertical axis wind turbine and construction of prototype turbine. The prototype will then go through experimental validation. The turbine was designed such that it can be connected to a generator and a torque transducer to measure the output power, torque and rotational speed of the turbine. The design will also allow for data collection power output capability.

1.7 Thesis Outline

The thesis is divided into five parts.

Chapter 1: Introduction. This chapter is on the background, problem statement and justification, research hypothesis, objectives and research questions.

Chapter 2: Review of Literature. This chapter presents a review of literature relevant to this study. A detailed overview of types of wind turbines and materials for wind turbine manufacture is presented. It outlines the principle of capturing wind energy and how turbines work.

Chapter 3: Materials and Methods. This chapter presents the key areas the study focuses on. It starts with the Theory and design optimization section that presents a numerical design process of the rotor blade and the relevant support theory including the design equation. A step by step numerical design process using Qblade modelling software is presented discussing key design parameters. A prototype is presented as the design process output. In the following section the design prototype is developed into a full scale H darrieus wind turbine with a detailed description of the materials and fabrication methods used.

Chapter 4: Results and discussion. The chapter starts with the rotor Performance testing and presents the performance of the full scale H darrieus wind turbine under various wind speed scenarios. A discussion on the viability of the VAWT and a cost benefit analysis and viability of the developed VAWT is also presented

Chapter 5: This chapter summarises the thesis conclusion

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Wind is the movement of the air between high pressure and low pressure regions in the atmosphere, caused by the uneven heating of the earth’s surface by the sun. When the air above hot surfaces is heated, it rises, creating a low pressure zone. The air surrounding higher pressure zones flows toward the low pressure area, creating wind. For this reason, sometimes wind energy is called “indirect solar energy.” (Paraschivoiu *et al.*, 2009). Because this mass of air is moving, it has energy, renewable energy that has been used to provide thrust to sailboats and ships crossing the oceans, to windmills used to pump water for irrigation or grinding up grain. Today, only a small fraction of the world's electricity is generated by wind, however, demand for this renewable energy resource will continue to increase with the depletion of fossil fuels.

As the world continues to use up non-renewable energy resources, wind energy will continue to gain popularity. A new market in wind energy technology has emerged that has the means of efficiently transforming the energy available in the wind to a useable form of energy, such as electricity. The cornerstone of this new technology is the wind turbine.

A wind turbine transfers fluid energy to mechanical energy through the use of blades and a shaft and converts that form of energy to electricity through the use of a generator. Depending on whether the flow is parallel to the axis of rotation (axial flow) or perpendicular (radial flow), determines the classification of the wind turbine. Each type of wind turbine has its strengths and weaknesses, but in the end, all wind turbines accomplish the same task.

2.2 Wind Turbine Types

Two major types of wind turbines exist based on their blade configuration and operation. The first type is the horizontal axis wind turbine (HAWT). This type of wind turbine is the most common and can often be seen littered across the landscape in areas of relatively level terrain with predictable year round wind conditions. HAWTs sit atop a large tower and have a set of blades that rotate about an axis parallel to the flow direction. These wind turbines have been the main subject of wind turbine research for decades, mainly because they share common operation and dynamics with rotary aircraft.

The second major type of wind turbine is the vertical axis wind turbine (VAWT). This type of wind turbine rotates about an axis that is perpendicular to the oncoming flow; hence, it can take wind from any direction. VAWTs consist of two major types, the Darrieus rotor and Savonius rotor. The Darrieus wind turbine is a VAWT that rotates around a central axis due to the lift produced by the rotating aerofoils, whereas a Savonius rotor rotates due to the drag created by its blades. There is also a new type of VAWT emerging in the wind power industry which is a mixture between the Darrieus and Savonius designs. Refer to figure 2.1 for various types of wind turbines

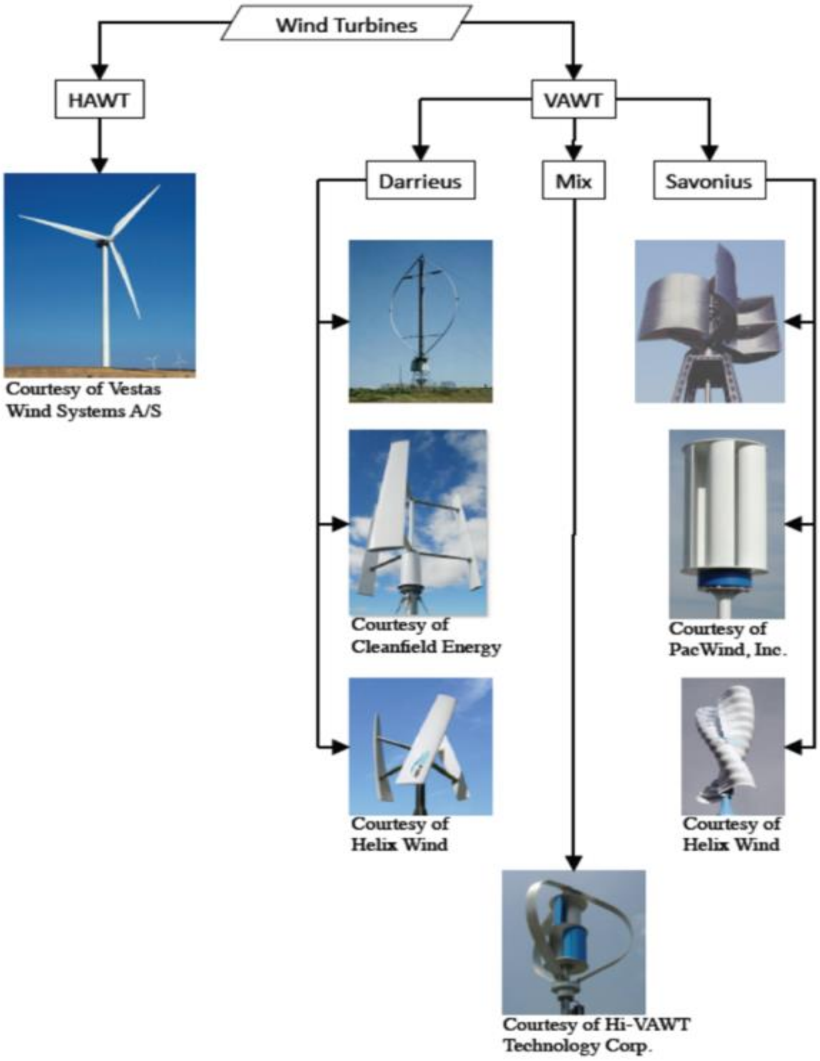


Figure 2.1: Types of wind turbines (Carrigan, 2010)

2.1.1 Horizontal Axis Wind Turbines

The HAWT is the most popular and widely used type of wind turbine. Companies such as Vestas, Siemens, and GE develop and deploy HAWTs around the world, making them the largest and most successful wind turbine manufacturers. Backing these companies is rock solid wind turbine technology based on the foundation and experience gained from propeller and rotary-wing aircraft. All major wind farms around the world employ many HAWTs working as a team to aide in the generation of electricity for small towns and large cities (Carrigan, 2010).

The blades of a HAWT work to extract energy from the wind by generating lift, resulting in a net torque about the axis of rotation. As the torque is produced through the slow turning of the wind turbine blades, the gearbox speeds up this rotation for the production of electricity through the use of a generator. To accomplish this task efficiently, especially for large HAWTs, active pitch controllers are used to ensure that each blade is adjusted to maintain an optimal angle of attack for maximum power extraction for a given wind speed. A yaw controller is also used to actively yaw the blades into the wind. However, these active control systems are complex and require more moving parts and effort to install than a VAWT assembly where the only moving part is the rotor, and the majority of components are located at the base of the turbine (Carrigan, 2010).

The design and manufacturing of a HAWT blade is complex as the blade is tapered and twisted with varying cross-sections in order to achieve optimum aerodynamic performance. A HAWT blade assembly can be seen in Figure. The change in the cross-section and twist of the blade from the root to the tip is due to the variation of the relative velocity component w. Because the tip of the blade spins much faster than the root, the twist of the blade is shallow and the cross-section is thin. It can be seen in the figure that due to the high relative velocity at the tip, the resultant force F acting on the blade section is extremely high, but only a small portion of that force Fd is driving the rotation. However, because of the blades design, the thin blade profile with a low angle of twist at the tip produces roughly the same amount of torque as the root of the blade due to its large moment arm. Because of the slower rotation speed at the root, the blade profile is much thicker with a higher angle of twist than at the tip. This design means a larger portion of the resultant force is in the direction of rotation. However, due to the lower moment arm at the root, the torque distribution over the entire blade is fairly uniform.

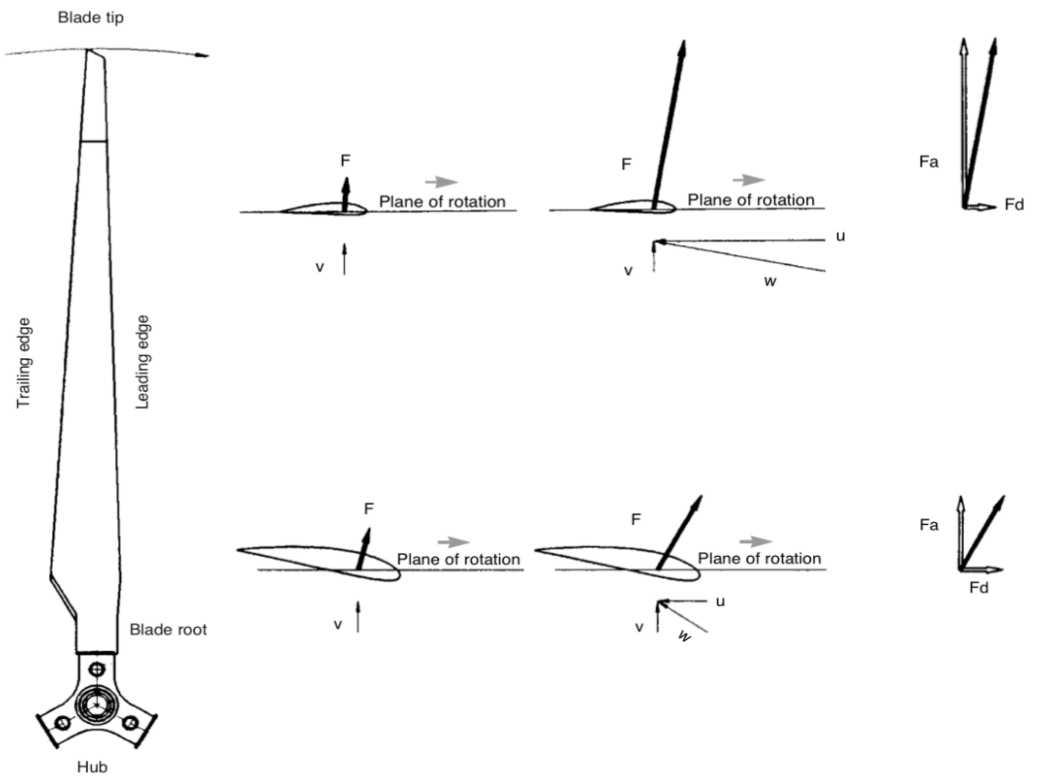


Figure 2.2: HAWT blade root and tip aerofoil sections (Carrigan, 2010)

2.1.2 Vertical Axis Wind Turbines

Recently, VAWTs have been gaining popularity due to interest in personal green energy solutions. Small companies all over the world have been marketing these new devices such as Helix Wind, Urban Green Energy, and Windspire. VAWTs target individual homes, farms, or small residential areas as a way of providing local and personal wind energy. This reduces the target individual's dependence on external energy resources and opens up a whole new market in alternative energy technology.

Because VAWTs are small, quiet, easy to install, can take wind from any direction, and operate efficiently in turbulent wind conditions, a new area in wind turbine research has opened up to meet the demands of individuals willing to take control and invest in small wind energy technology.

The device itself is relatively simple. With the major moving component being the rotor, the more complex parts like the gearbox and generator are located at the base of the wind turbine. This makes installing a VAWT a painless undertaking and can be accomplished quickly. Manufacturing a VAWT is much simpler than a HAWT due to the constant cross section blades. Because of the VAWTs simple manufacturing process and installation, they are perfectly suited for residential applications (Carrigan, 2010).

The VAWT rotor, comprised of a number of constant cross-section blades, is designed to achieve good aerodynamic qualities at various angles of attack. Unlike the HAWT where the blades exert a constant torque about the shaft as they rotate, a VAWT rotates perpendicular to the flow, causing the blades to produce an oscillation in the torque about the axis of rotation (Jamieson, 2011).This is due to the fact that the local angle of attack for each blade is a function of its azimuthal location. Because each blade has a different angle of attack at any point in time, the average torque is typically sought as the objective function. Even though the HAWT blades must be designed with varying cross-sections and twist, they only have to operate at a single angle of attack throughout an entire rotation. However, VAWT blades are designed such that they exhibit good aerodynamic performance throughout an entire rotation at the various angles of attack they experience leading to high time averaged torque. The blades of Darrieus VAWT (D-VAWT) accomplish this through the generation of lift, while the Savonius type VAWTs (S-VAWT) produce torque through drag. A snapshot of the cross-section of a D-VAWT blade can be seen in figure 2-3.

An S-VAWT generates electricity through drag rather than lift like the D-VAWT. A cross-section of a Savonius wind turbine can be seen in Figure. As the wind hits the concave portion of the blade (the bucket), it becomes trapped and pushes the blade around, advancing the next bucket into position. This continues as long as the wind is blowing and can overcome the friction of the shaft about which the blades rotate

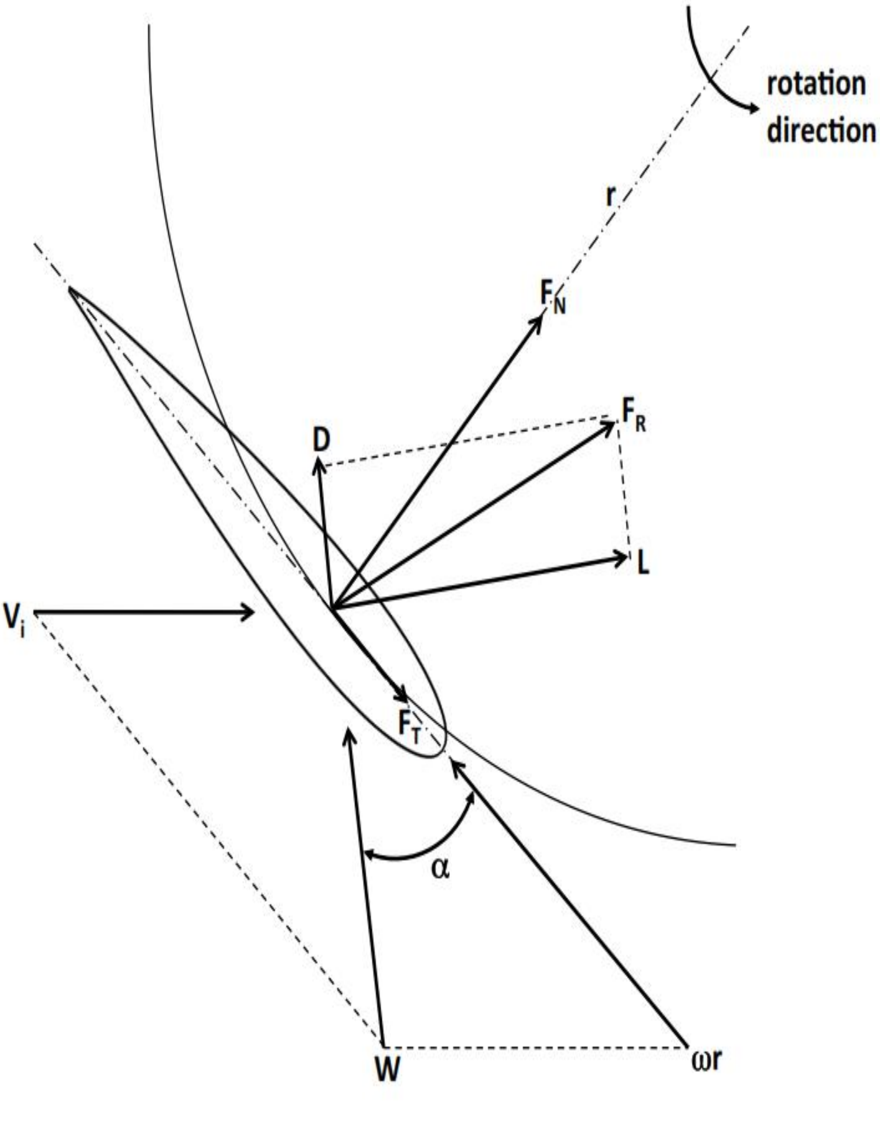


Figure 2.3: Velocity and force components for a Darrieus type VAWT (Carrigan, 2010)

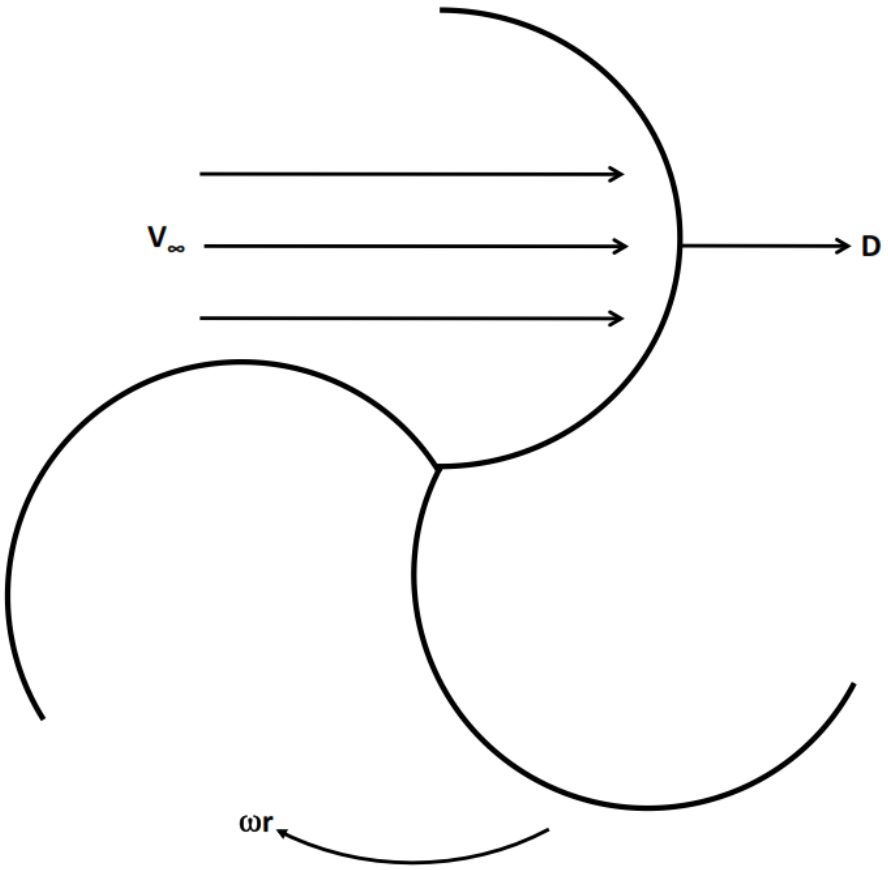


Figure 2.4: Velocity and force components for a Savonius type VAWT (Carrigan, 2010).

A Savonius rotor typically rotates with a velocity equivalent to the speed of the freestream velocity, or a tip speed ratio of one because of its lower rotation speed, Savonius rotors are associated with lower efficiencies and are not capable of providing adequate electricity, but rather serve as a device used to reduce the overall dependence on other energy resources. However, due to the Savonius wind turbines simplicity, it is extremely easy to construct; some have even been built using large plastic blue polydrums with the capability of providing up to 10% of a household's electricity (Percival *et al*., 2004).

2.3 Materials for small wind turbine manufacture

The blades in a normally operating wind turbine rotor are continuously exposed to cyclical loads from wind and gravity. The expected lifetime for a blade is usually 20 years for large wind turbines, and less than 20 years for small wind turbines (Clausen, *et al*,. 2000). Based on these conditions, Holmes *et al*. (Holmes *et al.,* 2007) summarized that the primary requirements for blade materials are high stiffness to ensure aerodynamic performance, low density to minimize mass and long-fatigue cycles. In the wind turbine industry, many materials have been used for blades, including metals, plastics, wood and composites (Manwell *et al.,* 2009).

2.2.1 Metal

Steel is a common, relatively inexpensive material used extensively in industry, however, it is difficult to manufacture into a complex twisted shape, and the fatigue life of steel is very poor compared to fibreglass composites (Burton *et al.,* 2006). While steel was used for wind turbines blades before the 1950s, it is essentially no longer used (Manwell *et al.,* 2009).

Another metal that has been considered for wind turbine blades is weldable aluminium. However, its fatigue strength at 10 cycles is only 17 MPa compared with fibreglass 140 MPa and carbon fibre 350 MPa (Burton *et al.,* 2006). Aluminium was sometimes used for small wind turbine blades, usually to produce non-twisted blades by protrusion (Manwell *et al.,* 2009). However, like steel, aluminium is little used in practice.

2.2.2 Glass and carbon fibre composites

While various materials have been applied successfully in wind turbine blades, fibreglass based composites predominate (Veers *et al.,* 2003). This is mostly because fibreglass is a low-cost and high tensile strength material. It is also easily knitted and woven into desired textiles to meet different engineering requirements (Manwell *et al.,* 2009). Usually the fibreglass is embedded within a plastic matrix to form a composite known as glass reinforced plastic (GRP).

Carbon fibre is also becoming more popular because it has higher modulus, lower density and higher tensile strength than fibreglass and it is less sensitive to fatigue

(Veers *et al.,* 2003). However, carbon fibre is more expensive than fibreglass and it is difficult to align the fibres to maintain good fatigue performance (Holmes *et al.*, 2007; Veers *et al.,* 2003).

Recently, there is increased use of hybrids combining glass and carbon together to achieve moderate mechanical performance with moderate cost. Also fibreglass and carbon/wood hybrids are currently promising materials options for blades (Veers *et al.,* 2003).

In composite structures, matrix, also called binder, is the resin used to hold fibres in position and make the blade strong. The most common thermoset matrices are unsaturated polyesters, vinyl esters and epoxies thermoplastics were also developed in the past, however, the performance of these materials, such as PBT and PET, are lower than thermosets (Veers *et al.,* 2003). At present, no commercial examples of thermoplastics being used for this engineering application has been found.

2.2.3 Wood and bamboo

Minimally processed natural bio composites such as wood and bamboo are particularly appealing to make the blades environmental friendly. Wood had been used to make wind turbine blades for a long time because wood has good strength for its mass, as long as the direction of wood structure is placed right (Manwell *et al.,* 2009). Also wood is widely applied in making wood epoxy laminates for large wind turbines, and reportedly none has failed in fatigue (Burton *et al*., 2006).

In a research done by (Clausen, 2004) fatigue testing was conducted on a 1 m blade for a wind turbine with rated power 600 W using two types of wood commonly available in Australia. The results illustrated that both radiata and hoop pine could meet the operational requirements, though there was difference in strength between the two woods. In addition, they predicted that wood should be suitable for blades for small turbines up to 5 KW capacity with 2.5 m blades. However, the manufacturing and selection of wood would be great problems, and it is very difficult to find wood with homogeneous quality free of knots (Clausen & Wood, 2000). Bamboo is well known to have good mechanical performance: it has greater fracture toughness, greater specific strength and modulus than woods such as birch (Holmes *et al.*, 2007). In addition, the processing cost is not high and bamboo grows quickly. Bamboo would be a good material for blade building. However, bamboo has to be incorporated into composites for wind turbine blade applications because single bamboo stalks are not big enough for a blade. In addition, the properties in different layers of bamboo may vary greatly, and there is a need for more tests to determine specific data (Holmes *et al.*, 2007).

2.2.4 Biocomposites

The other method to utilize biomaterials is to develop bio composites. There are two main areas of research related to the use of bio composites in wind turbine blades. The first is to develop natural fibres that can partially or fully replace fibre glass and the other is to extract natural hemp fibre whose stiffness is close to that of fibre glass, but the tensile strength is much lower to (Thygesen *et al.*, 2006). Cellulose fibre can also be a promising material for future blades; the stiffness of cellulose fibre (80 GPa) is a little higher than fibre glass (72 GPa) whereas its tensile strength (1000 MPa) is much lower than fibre glass (3500 MPa) though the specific kind of cellulose fibre examined was not detailed (Brøndsted *et al.*, 2005).

A study tested three types of nature fibres for composite of wind turbine blades: flax unidirectional (UD) weave, flax twill weave and hemp mat, selected from a broad set of candidate fibres. It was found that flax UD weave was the best material for small wind turbine blade building. Vacuum moulding was used to construct a 3 m length blade, and press moulding for a 1.2 m length blade. The 1.2 m blade was built successfully and met the static test requirement, however, the 3 m blade failed in fabrication. The study concluded that natural fibres can be applied in small wind turbine blades with current manufacturing technologies (Frohnapfel *et al.*, 2010).

The second approach is to develop bio-resins to partially or fully replace the petroleum-based resin in the composite. Two types of bio-resin were tested; an epoxidized soybean oil (AESO) resin and a polylactic acid (PLA) resin; the results showed that AESO works better than PLA though both need to be studied more. In addition, NIMRC is developing epoxidase soya oil (ESO) and a natural resin purified from Venonia plant (Akesson *et al.,* 2006).

2.4 Manufacturing of small wind turbine blades

There are many manufacturing methods for small wind turbine blades in the literature. The choice of manufacturing methods basically depends on the materials specified, and size and aerofoil of the blade as well as economic considerations. Large wind turbine blades often use a sandwich structure and are usually more complex than the small ones. Only the methods appropriate for small wind turbine blades are discussed here.

For a pure wood blade, milling a wood blank to the correct blade shape is a feasible, direct method. Arix CNC 90 three-axis milling machine can be used to produce 1 m long blades (Clausen, 2004). However, the material efficiency of this approach is low and the cost is high. If the wood is found to have a knot or other defects, the blade must be discarded and a new one should be fabricated. Also the effort needed to ensure close tolerances and a good surface finish of the blade is significant and must be considered (Clausen & Wood 2000).

Hand-lay-up, in which layers of fibreglass or other cloth are cut and placed by hand and infused with resin, is a very popular method for building fibre and wood-epoxy composites. It is a traditional technique used in boat building for many decades and has been successfully applied to wind turbine blade building (Brøndsted *et al.,* 2005). The method is relatively simple, but requires a large amount of labour and since the quality of the product depends on the skill of the builder; it is difficult to reliably ensure high strength.

Filament winding is a method used in the aerospace industry which is also popular in wind turbines (Brøndsted *et al.,* 2005; Manwell *et al.,* 2009). This method is used with fibreglass composites or similar materials. The principle is to wind the glass fibres around a mandrel while resin is placed on simultaneously. The method can be performed automatically. One shortcoming is that it cannot be applied to concave aerofoils: many newly developed aerofoils for small wind turbines include concave surfaces (Clausen & Wood 2000; Manwell *et al.,* 2009).

Pultrusion, in which glass fibres are pulled through resin and then a heated die in the shape of the aerofoil cross section, is a relatively inexpensive way to mass produce blades; however, it is limited to untwisted, untapered blades. Bergey Windpower uses this method to produce their wind turbine blades (Clausen & Wood 2000) including the blades for the Bergey XL 1.0. Bergey's wind turbines with these blades range in capacity from 1.0 KW to 10 KW (Bowen *et al.,* 2003).

The largest US small wind turbine manufacturer, Southwest Windpower, produces the blades for their small Air X wind turbine (capacity 400 W to 600 W) using injection moulding. This turbine blade is made of carbon fibre (Anon n.d.). Clausen and Wood (Clausen & Wood 2000) used Resin Transfer Moulding (RTM) to build two types of blades for 5 KW and 20 KW wind turbines respectively. Injection moulding and RTM are resin infusion technologies which can be used to obtain consistent quality, and would be suitable for small wind turbine blades using all aerofoil types (Brøndsted *et al*., 2005).

2.5 How Wind Energy is harnessed

Turbines relying on drag, such as the anemometer and Savonius models, cannot spin faster than the wind blows and are thus limited to a TSR of less than 1. Other turbines, such as the Darrieus, rely on lift to produce a positive torque. Lift type wind turbines can experience TSR as high as 6. This is possible because the natural wind is vector summed with the wind opposing the forward velocity of the aerofoil. This combined velocity is known as the relative wind.

2.6 How Turbines Work

The wind imposes two driving forces on the blades of a turbine; lift and drag. A force is produced when the wind on the leeward side of the aerofoil must travel a greater distance than that on the windward side. The wind traveling on the windward side must travel at a greater speed than the wind traveling along the leeward side. This difference in velocity creates a pressure differential. On the leeward side, a low-pressure area is created, pulling the aerofoil in that direction. This is known as the Bernoulli's Principle. Lift and drag are the components of this force vector perpendicular to and parallel to the apparent or relative wind, respectively. By increasing the angle of attack (Islam *et al.*, 2007), as shown in Figure , the distance that the leeward air travels is increased.

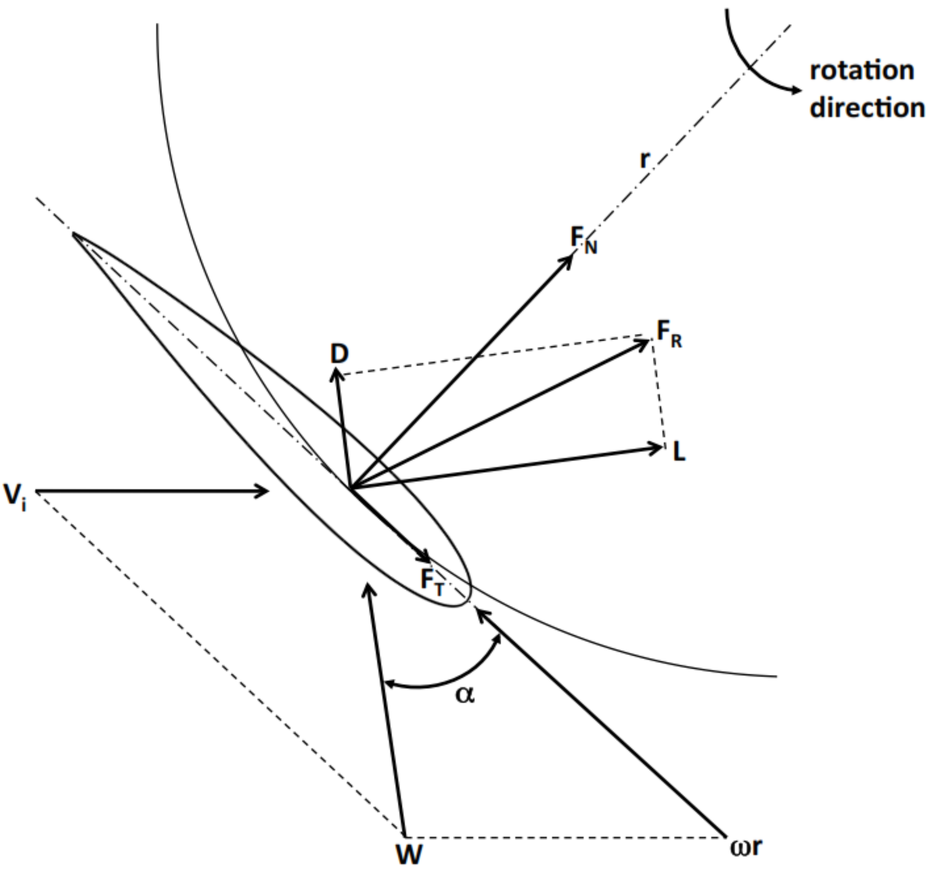


Figure 2.5: Velocity and force components for a Darrieus type VAWT

(Carrigan 2010).

This increases the velocity of the leeward air and subsequently the lift. Lift and drag forces can be broken down into components that are perpendicular (thrust) and parallel (torque) to their path of travel at any instant. The torque is available to do useful work, while the thrust is the force that must be supported by the turbine's structure.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Theory and Design Optimization

3.1.1 Turbine size as a function of power required

The power of the wind is proportional to air density, area of the segment of wind being considered, and the natural wind speed. The relationships between the above variables are provided in equation 1 below (Johnson, 2001).

$$\boldsymbol{P_w = 0.647\rho A u^3} \text{ ....1}$$

Pw: power of the wind *(W)*

ρ : air density *(kg/m3)*

A: area of a segment of the wind being considered (*m²)*

u: undisturbed wind speed (*m/s*)

At standard temperature and pressure (STP = 273K and 101.3 KPa), equation 3.1 reduces to equation 2:

$$\boldsymbol{P_w = 0.647 A u^3} \text{ ....2}$$

A turbine cannot extract 100% of the winds energy because some of the winds energy is used in pressure changes occurring across the turbine blades. This pressure change causes a decrease in velocity and therefore usable energy. The mechanical power that can be obtained from the wind with an ideal turbine is given in equation 3:

$$P_m = \frac{1}{2}\rho\left(\frac{16}{27}\right)Au^3 \text{..} 3$$

Where;

P_m: mechanical power (W)

In equation 3, the area, A, is referred to as the swept area of a turbine. For a VAWT, this area depends on both the turbine diameter and turbine blade length. For an H-type VAWT the equation for swept area is:

$$A_s = D_t l_b \text{..} 4$$

Where;

A_s: swept area *(m²)*

D_t: diameter of the turbine *(m)*

l_b: length of the turbine Blades *(m)*

The constant 16/27 = 0.593 from equation 3 is referred to as the Betz coefficient. The Betz coefficient tells us that 59.3% of the power in the wind can be extracted in the case of an ideal turbine (Paraschivoiu *et al.*, 2009). However, an ideal turbine is a theoretical case. Turbine efficiencies in the range of 35-40% are very good, and this is the case for most large-scale turbines. It should also be noted that the pressure drop across the turbine blades is very small, around 0.02% of the ambient air pressure.

Equation 3 can be re-written as;

$$P_m = C_p P_w \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{5}$$

Where *Cp:* coefficient of performance.

The coefficient of performance depends on wind speed, rotational speed of the turbine and blade parameters such as pitch angle and angle of attack. The pitch angle for a HAWT is the angle between the blades motion and the chord line of the blade, whereas for a VAWT the pitch angle is between the line perpendicular to the blades motion and the chord line of the blade. The angle of attack is the angle between the relative wind velocity and the centreline of the blade. For fixed pitch turbines, these angles do not change and the C_p is directly related to the TSR. See Table below for typical C_p values for various types of wind turbines (Kojabadi *et al.*, 2004).

Table 3.1: Typical Cp values for various wind turbines (chang *et al.*, 2005)

Wind System	**Efficiency %**	
	Simple Construction	Optimum Design
Multi bladed water pump	10	30
Sail wing water pump	10	25
Darrieus water pump	15	30
Savonius Wind pump	10	20
Small prop-type wind charger (up to 2 KW)	20	30
Medium prop-type wind charger (2 to 10 KW)	20	30
Small prop-type wind charger (over 10 KW)		30 to 45
Darrieus wind Generator	15	20

3.1.2 Turbine Solidity as a Function of TSR

The operating tip–speed ratio (TSR) for a Darrieus rotor lies between 4 and 6 (DeCoste *et al.,* 2005). This design TSR then determines the solidity, gear ratios, generator speeds, and structural design of the rotor. Using this TSR and the graph in Figure, a value of the solidity is selected. As with the prop–type rotor, the solidity allows for the calculation of blade area. Solidity times the rotor frontal area gives the total blade area. Dividing the total blade area by the number of blades (usually 2 or 3) gives the individual blade area. The individual blade area divided by the rotor height gives the chord length (Kojabadi *et al.*, 2004).

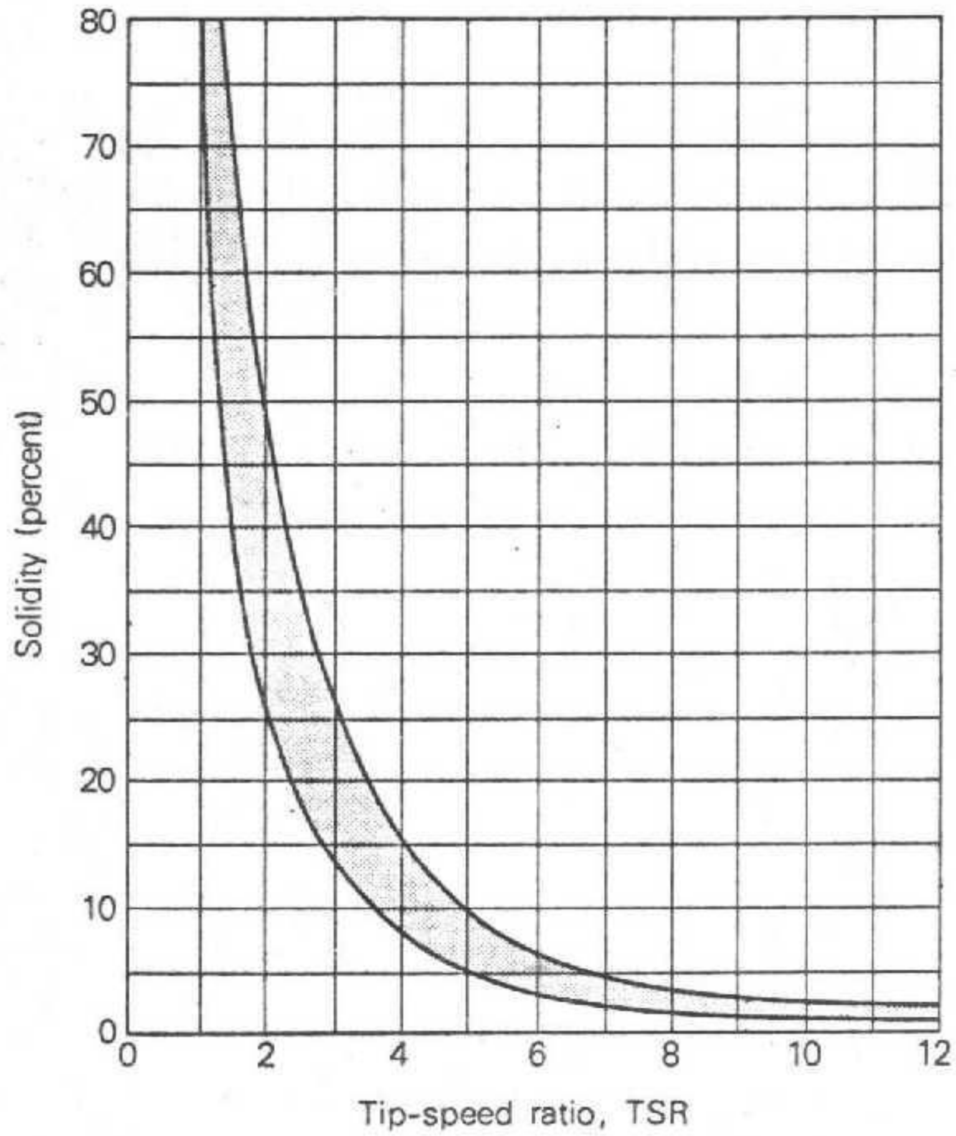


Figure3.1: Rotor solidity as a function of TSR (Jack Park, 1981)

3.1.3 Turbine Model Calculation

This section outlines the calculations used by the Qblade software to model the turbine blades. First, the Reynolds number associated with the flow over the aerofoils is determined by equation 6.

$$\boldsymbol{R_e = \frac{W \times TSR \times \rho_{air} \times cl}{v_{air}}} \text{...} \mathbf{6}$$

Where;

Re: Reynolds number

W: Wind speed *(m/s)*

TSR: Tip speed ratio

Pair: Density of air

Cl: chord length

Vair: Viscosity of air *Ns/m²*

Since the turbine spins about a central shaft, the wind speed that the blades experience is not equal to the ambient wind speed. The angle of attack of the turbine blades continuously changes throughout the blades 360° Revolution. As a result, the magnitude of the relative wind speed changes throughout the rotation, and this is the parameter used to calculate the Reynolds number as given in equation 2.6. Furthermore, since the relative wind speed changes for each degree of the 360°revolution, and it also changes for different values of TSR, it would be monotonous and cumbersome to carry out the calculations for relative wind speed manually. To avoid iterative calculations, Qblade open source turbine calculation software that is seamlessly integrated into XFOIL automatically calculates the angles of attack and the relative wind speeds for a specified TSR throughout the revolution of 0° to 360°

The model uses the relative wind speed as specified by Qblade to calculate the Reynolds number as given by equation 6. After the Reynolds number is calculated, the lift and drag coefficients were obtained from the NACA 0021 coefficients look up table *(refer to appendix C). However, lift and drag coefficients are dependent on the Reynolds number and the angle of attack. To calculate the angle of attack, the angle specified from the Qblade program is added to the desired blade pitching angle of attack, as specified in the model inputs. Once the actual angle of attack is determined, the model uses the Reynolds number along with the angle to lookup the appropriate lift and drag coefficients. Upon determining the lift and drag coefficients, the lift and drag forces are calculated using equations 7 and 8, respectively.

$$\boldsymbol{F_l = \frac{1}{2}\rho_{air}W^2 \times cl \times bl \times C_l} \text{ ……………………………………..7}$$

$$\boldsymbol{F_d = \frac{1}{2}\rho_{air}W^2 \times cl \times bl \times C_d} \text{ ………………………………………8}$$

where

F_l: Lift Force (N), F_d: Drag force (N), *TSR*: Tip speed ratio, *bl*: Blade length (m), *Cl*: Lift Coefficient, *Cd*: Drag coefficient

The lift and drag forces are then resolved into components parallel and perpendicular to the blades' path of rotation. Equations 9 to 12 are used to resolve the lift and drag forces into parallel and perpendicular components.

$$\boldsymbol{F_{l,help} = F_l \cos\left[\left(\frac{90\,\pi}{180}\right) - \left(\frac{\alpha_{actual}\pi}{180}\right)\right]} \text{……………………………… 9}$$

$$\boldsymbol{F_{l,circ} = F_l \sin\left[\left(\frac{90\,\pi}{180}\right) - \left(\frac{\alpha_{actual}\pi}{180}\right)\right]} \text{ ……………………..…….10}$$

$$\boldsymbol{F_{l,hurt} = F_d \cos\left(\frac{\alpha_{actual}\pi}{180}\right)} \text{ …………………………………………..11}$$

$$\boldsymbol{F_{l,circ} = F_d \sin\left(\frac{\alpha_{actual}\pi}{180}\right)} \text{ …………………………..…………….12}$$

Where;

Fl;help : Force in direction of travel (N)

F l;circ: Force contributing to centrifugal force (N)

F d;hurt: Force opposing motion of blade travel (N)

F d;circ: Force contributing to centrifugal force (N)

αActual: Angle of attack with added pitching (rad)

Parallel and perpendicular forces are added in their respective directions to obtain expressions for F_1 and F_2, as given by equations 13 and 14

$$\boldsymbol{F_1 = F_{l,help} - F_{d,hurt}} \quad \text{...}\mathbf{13}$$

$$\boldsymbol{F_2 = F_{l,circ} - F_{d,circ}} \quad \text{..}\mathbf{14}$$

Where;

F_1: forces contributing to torque (N), F_2: centrifugal forces (N)

3.1.4 Rotor design Process

The flow chart in figure below summarizes the rotor blade design process

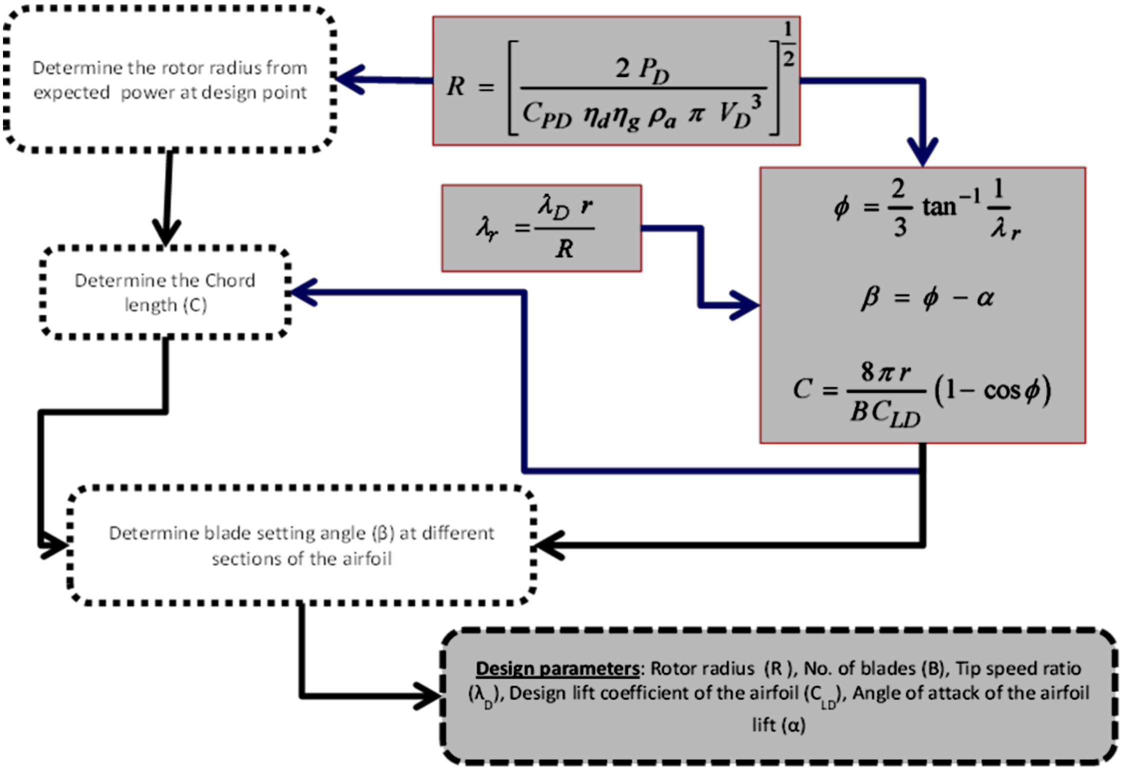


Figure 3.2: Rotor blade design process (Manwell *et al.*, 2009)

3.1.5 Fixed parameters

All the design parameters are not free. Some can be chosen freely by the designer, such as the rotational speed as function of the wind speed (namely the maximum rotation speed allowed). Other parameters are held fixed to shorten the amount of time needed. Following parameters are held fixed:

- Number of blades: 3

- Optimum TSR: 4

- Blade profile type restricted to symmetrical airfoils

- Struts blade profile: NACA 0021

The choice of three blades is mainly motivated by the reduction in complexity. An optimum TSR of 4 is chosen as it is in the range of earlier VAWT designs and has proved to be viable for the prototype turbine.

3.1.6 Qblade modelling software

QBlade is an open source wind turbine calculation software, distributed under the GPL. The integration of the XFOIL/XFLR5 functionality allows the user to rapidly design custom airfoils and compute their performance polars and directly integrate them into a wind turbine rotor design and simulation (Qblade. (n.d.)

The software is especially adequate for teaching, as it provides a 'hands on' design and simulation capabilities for HAWT and VAWT rotor design and shows all the fundamental relationships of design concepts and turbine performance in an easy and intuitive way Qblade. (n.d.).

QBlade also includes extensive post processing functionality for the rotor and turbine simulations and gives deep insight into all relevant blade and rotor variables. In addition to that, the resulting software is a very flexible and user-friendly platform for wind turbine blade design. Basic Qblade functionality include Qblade. (n.d.);

- Extrapolation of XFOIL generated or imported polar data to 360° AoA
- Blade design and optimization, including 3D visualization, using XFOIL generated or imported profiles
- Turbine definition (rotor blade, turbine control, generator type, losses...)
- Computation of rotor performance over lambda (tip speed ratio) range
- Turbulent inflow field generator according to the model of Veers.
- Computation of rotor performance over lambda (tip speed ratio) range
- Computation of turbine performance over wind speed range

- Annual yield computation based on custom Weibull distribution>
- Manual selection of BEM (Blade Element Momentum) and DMS (Double Multiple Streamtube) correction algorithms
- Multi parameter rotor simulations.
- Data browsing and visualization as post processing
- Export functionality for all created simulation data
- Blade geometry export functionality
- Storing of projects, rotors, turbines and simulations in a runtime database
- Integration of the aeroelastic code AeroDyn/FAST of the National Renewable Energy Laboratory (NREL)

3.1.7 Designing of the Rotor Blade

The Qblade software, described in section 3.1.6, does not find an optimal design automatically because a global optimum may not exist. Therefore, a first guess is needed to start optimizing and save time. Based on intended application of the turbine at a simple rural homestead Smaller wind systems (500W) can for example serve electrical power to households, who require modern energy for lighting, TV, charging devices etc. Table 3.2 gives a typical load demand of a rural small household. As can be observed from the table, the total energy demand in this case is 260Wh,

which means that this household has a constant power demand of 260W for one hour a day.

Table 3.2: Typical Kenyan household energy demand (GVEP International)

Component	Power (W)	Time (Hrs / day)	Energy (Wh)
Phone charger	1	60	60
TV	75	1	75
Lighting	25	5	125
Energy requirement per day			260

Some parameters can therefore be deduced using the wind power equation to come with start up the design procedure. For a H-rotor with a power output of 500W turbine rated at 12 m/s a rotor with approximately a radius of 1m and a blade length of 1.6m was selected. All other parameters listed in section 3.1.5 are held the same. These dimensions are based on the tentative design procedure which approximately suggests a turbine of this size (see section 3.1.5). Table 3.3 summarize the parameters of the selected design

The optimal TSR (TSR at optimal C for use in the variable speed range) has been set to four. The maximum blade tip speed has been set to 40 m/s. Three blades are used in order to reduce the structural load variations without affecting the overall performance.

The design is tested for variations in solidity, blade profile thickness, fixed blade pitch and point of attachment in mentioned order. When choosing the turbine with best performance, not only Cp at the optimal TSR concludes what design that performs the best. In most of the design steps, the lift- and drag coefficients as well as the tangential and normal forces transferred to the struts are studied to avoid unfavourable characteristics.

A Model was then developed using Qblade. The wind speed was kept constant throughout the engineering analysis at the average wind speed value for of 6 m/s since the purpose of the application was to take advantage of the average wind speed rather than higher speeds, which are not so frequent.

Table 3.3: Selected design parameters

Undisturbed Wind Speed	6 m/s
Density of air	1.204 kg/m³
Viscosity of air	1.81×10^{-05} Ns/M²
Rated wind speed	9 m/s
TSR	4
Solidity	0.15
Rotor Diameter	2 m
number of aerofoils/blades	3
Blade length/height	1.60 m
NACA air foil	0021
Estimated coefficient of performance	0.1
Blade chord length	Will be optimized
Fixed pitch angle	Will be optimized

3.1.8 Aerofoil selection

The aerofoil was selected considering the availability of aerofoil data for angles of attack between -30 and 30º and the final thickness of the blade which is associated with its ability to withstand the loads. Only symmetrical NACA profiles were considered because of the significantly reduced costs associated with production of symmetrical profiles compared to cambered profiles. The higher production costs of cambered profiles is due to the necessity of constructing two molds to produce the up- and downside of the blade profile. Moreover, symmetric profiles are derived from polynomial shapes which make them easier to construct.

The available aerofoils with enough data to conduct the study of the aerodynamic loads and behaviour of the wind turbine were available in a document issued by Sandia National Laboratories (Sheldahl & Klimas 1981). This document provides the lift and drag coefficients depending on Reynolds number and angle of attack ranging from 0 to180 for several NACA aerofoils.

The selected aerofoil is the NACA0021, which aerodynamics characteristics were determined using an aerofoil property synthesizer code. This profile is one of the thickest available (21% of chord). NACA 0021 profiles is also able to withstand centrifugal loads and extreme aerodynamic loads. The actual shape of the NACA0021 is shown in figure 3-3 below

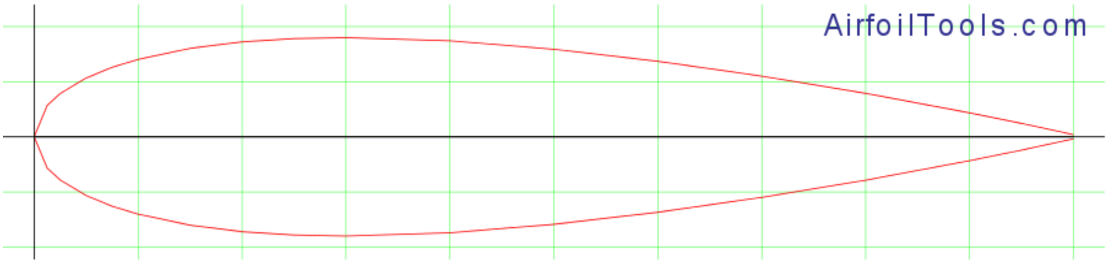


Figure 3.3: Naca airfoil 0021 profile.

Source http://airfoiltools.com/airfoil/details?airfoil=naca0021-il

The aerofoil selection can be also be done using an aerofoil simulation program like RFOIL, but problems may arise when trying to accurately predict the aerofoil behaviour at Reynolds numbers lower than 1.106 (Claessens, 2006).

3.1.9 Optimizing Solidity

In the analysis of the optimum solidity the chord length for the blade profiles is varied. The rest of the parameters in the reference design are held fixed. The TSR is fixed and equals four. Numerical Experiments with the Qblade model was performed. The results suggest that lower solidity generates a wider operating range in means of TSR's. A higher solidity generally makes the structure endure higher stresses and achieve maximum aerodynamic efficiency at lower TSR's. Figure 3-4 present the Cp vs. TSR curve for an H-rotor in the same range of Reynolds number.

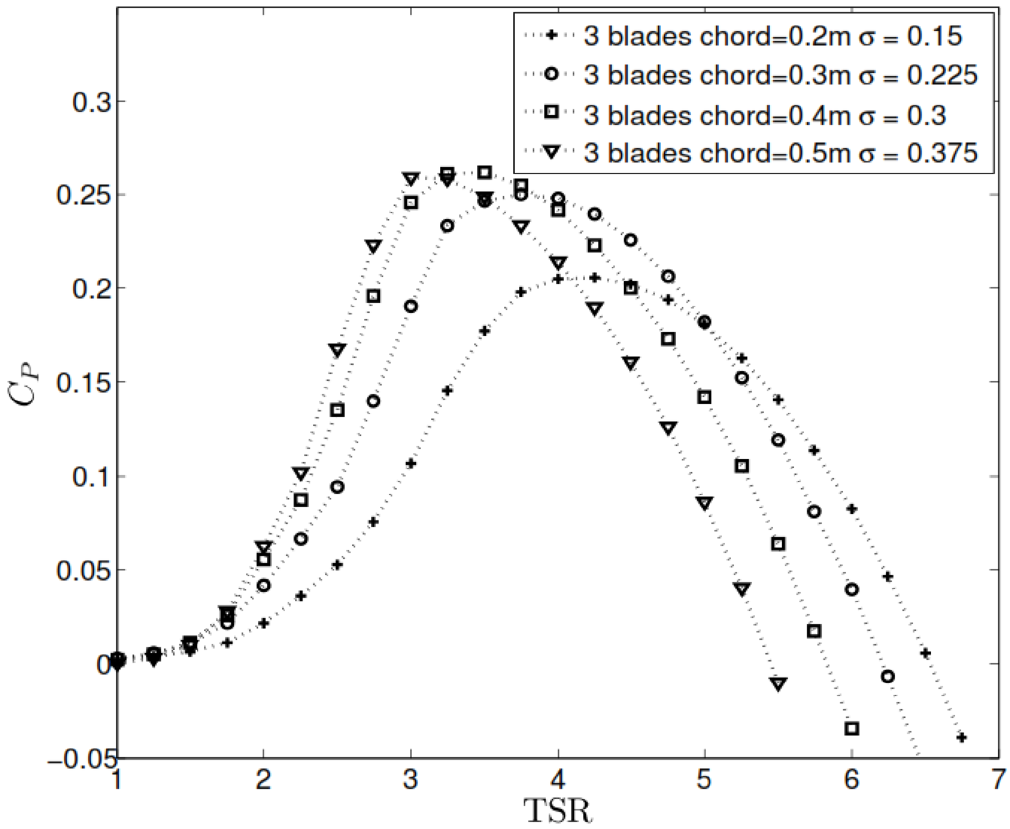


Figure 3.4: Cp vs. TSR curve for an H-rotor in the same range of Reynolds number.

Based on the results using the Qblade model a solidity of 0.27 is chosen, which implies a blade chord of 0.2m. This solidity can meet the demand of a strong structure

3.1.10 Optimizing fixed blade pitch

In the analysis of the optimum fixed blade pitch the offset angle is varied from 0 to +4 degrees. Positive pitch angles are defined as toe out. Early tests showed that all negative fixed pitch angles generated very bad results along with unfavourable load cycles. The TSR is varied for every blade profile between two and six. The blade chord length is set to 0.2m and the blade profile is set to NACA 0021. The rest of the parameters in the reference design are held fixed.

Sandia National Laboratories have done tests on a 5m radius research turbine concerning the effects of fixed blade pitch (paraschivoiu,2002). Significant variations in cut-in TSR, aerodynamic efficiency and maximum power output have been shown. Changes as small as only one or two degrees can generate large differences in result (Klimas *et al*,.1981). aerodynamic performance is changed when using a fixed blade pitch due to following reasons (Klimas *et al*,.1981):

The impact of pitching the blades has been investigated by doing several simulations with the Qblade model. Results from simulations using a NACA 0021 airfoil are shown in figure 3-5

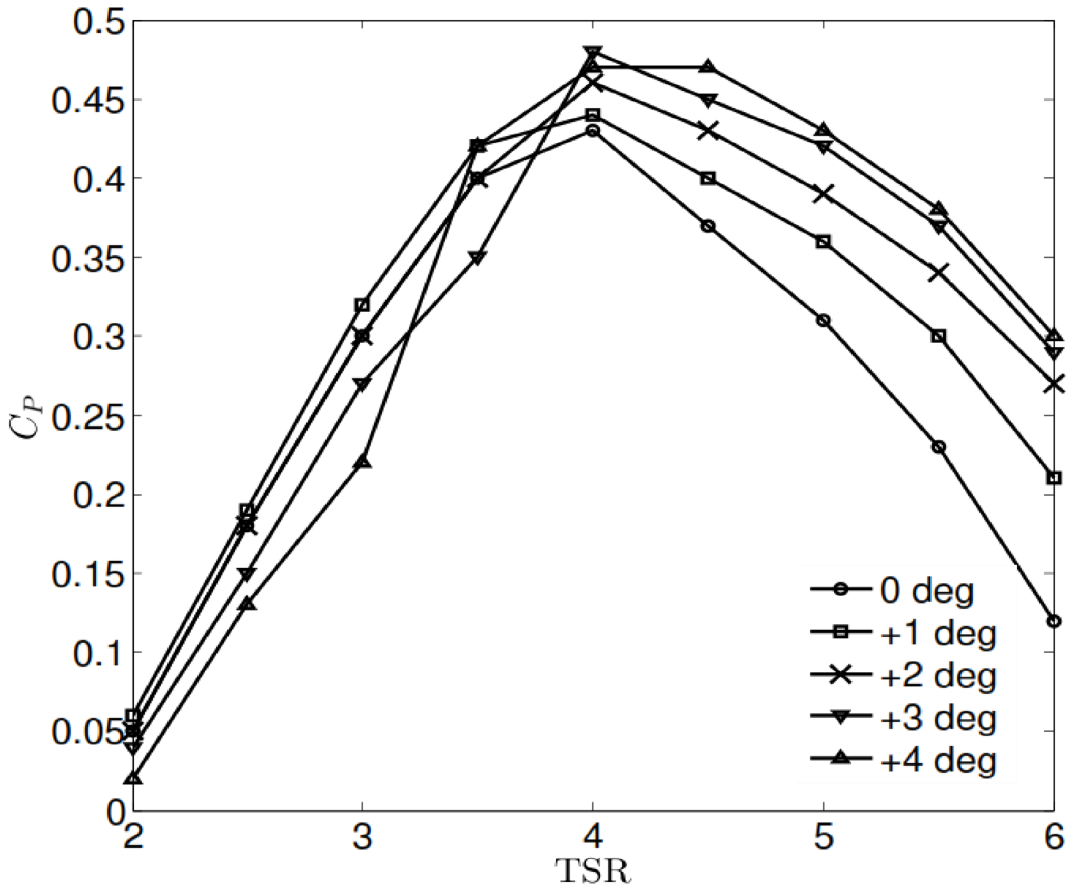


Figure 3.5: CP vs. TSR for a NACA 0021 and chord 0.2m with varying fixed pitch angle.

A pitched blade achieves a much higher aerodynamic efficiency, especially around the region of optimal TSR. The major explanation for this seems to be the possibility to move the region of blade stall around the blade revolution.

Based on these results a constant pitch of +4 degrees looks promising for the prototype. From an operation point of view, it is preferable to have a wide and smooth Cp vs. TSR curve in the region around the optimal tip speed ratio.

3.1.11 Rotor dimensions

The bigger blade length and rotor radius the bigger the torque produced. These parameters are involved also in the solidity calculation. The solidity becomes an important parameter when scaling down or up wind turbines and also determines the applicability of the momentum model (Castillo, 2011).

The radius and blade variation analysis was done maintaining constant swept area. It can be seen in figure 3-6 that an increase in rotor radius leads to greater maximum power coefficients, but they are achieved at greater tip speed ratios, so the little the radius, the less tip speed ratio is necessary to work at maximum power coefficient.

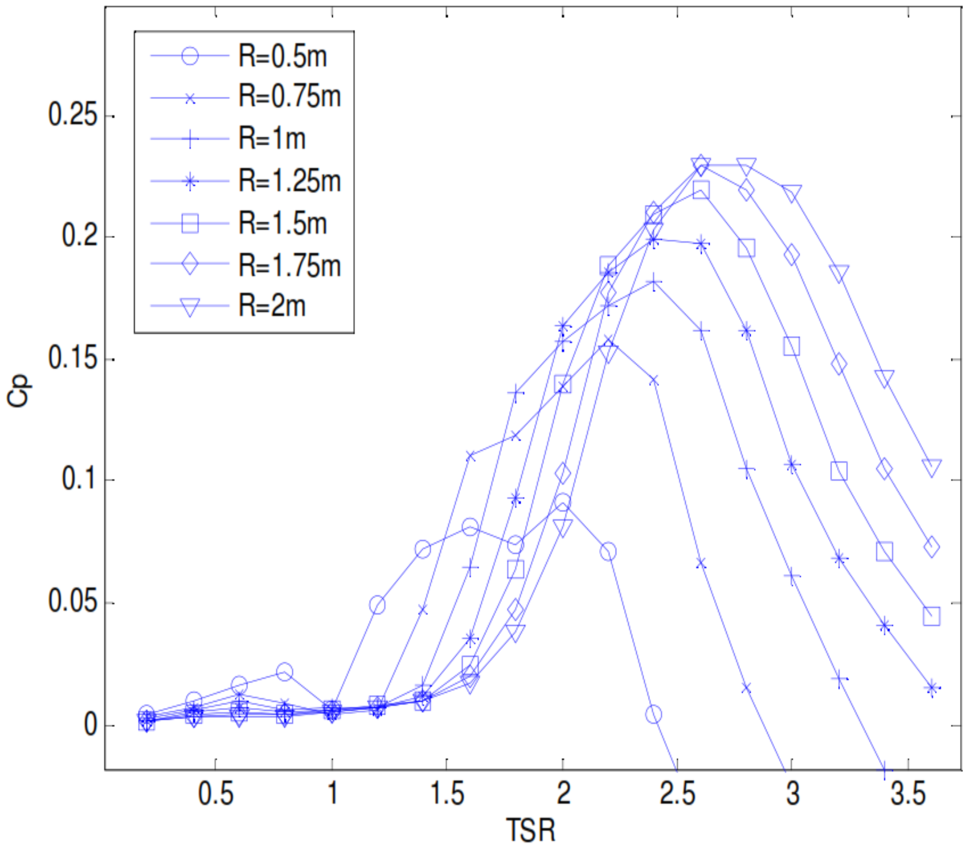


Figure 3.6: Cp dependent on rotor radius (R) and TSR maintaining constant Swept area.

The power coefficient is not affected by a sole variation of the blade length. This is deduced if the equation for calculating the power coefficient is developed and simplified Equation 15, in this case the upwind power coefficient is illustrated, but the dependences are equal on the downstream half. We can see blade length is present both in the numerator and denominator of the equation.

$$C_{pu} = \frac{Nc\omega \int_{\frac{\pi}{2}}^{\frac{\pi}{2}} CtW^2 d\theta}{4\pi Vo^3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 15$$

The rotor radius R is simplified also from the equation but it is still implicit in the calculation of the relative velocity W, so we can state that the rotor radius has influence both in torque (see figure 3-6) and power coefficient.

Nevertheless, the torque is affected by the blade length the same way the tangential force coefficient is dependent on the blade surface. Thus the blade length only affects torque and its optimization has to be done considering other factors as the swept area, which determines the power available from wind.

The blade tip losses are not contemplated in the model, so in a real model, an increase on blade length should make the blade more efficient. The optimization needs the input of a fourth factor, the maximum load due to both aerodynamic loads and rotational speed, as the radius will be the one determining them.

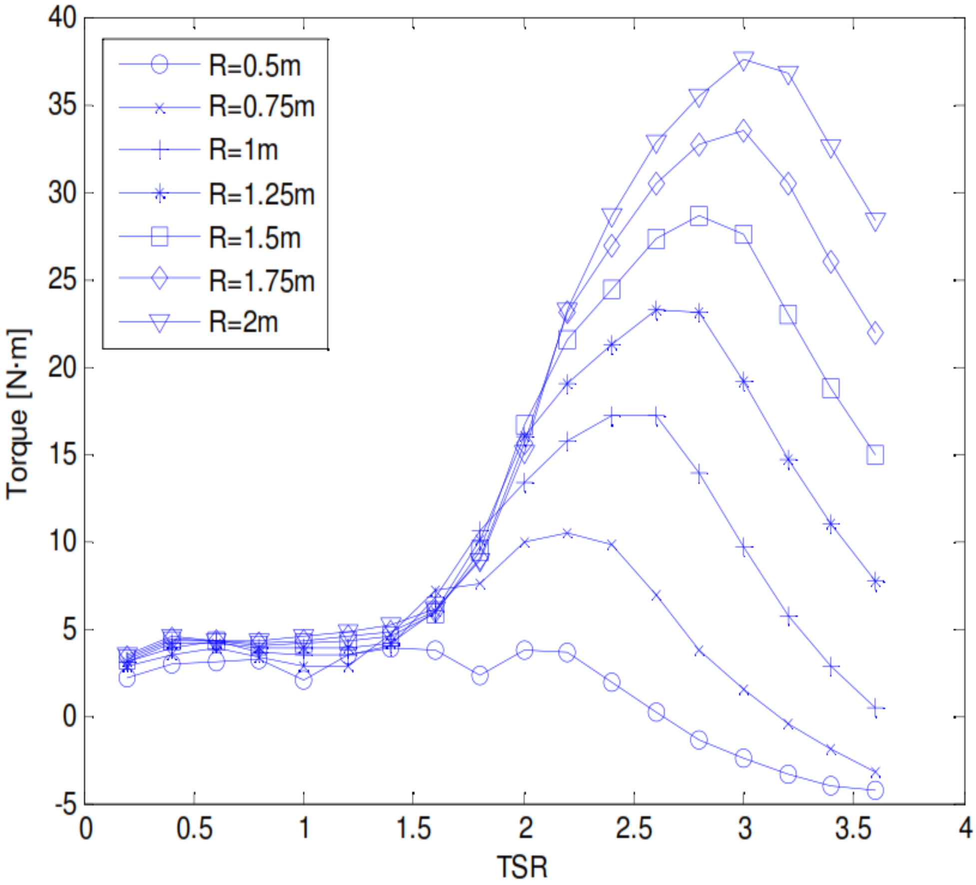


Figure 3.7: Torque dependent on rotor radius (R) and TSR maintaining constant Swept area.

3.1.12 Initial angle of attack

A positive initial angle of attack broadens the range of angular speed operation and a negative one shortens it (see figure 3-8); this is necessary when fixing the maximum RPM. Furthermore, the torque is influenced the same way resulting in a lower maximum power coefficient and torque for negative angles of attack.

The initial angle of attack for the design was set at 0 degrees as the advantages of a different angle of attack are, according to this model, only evident at higher tip speed ratios than the intended for the model.

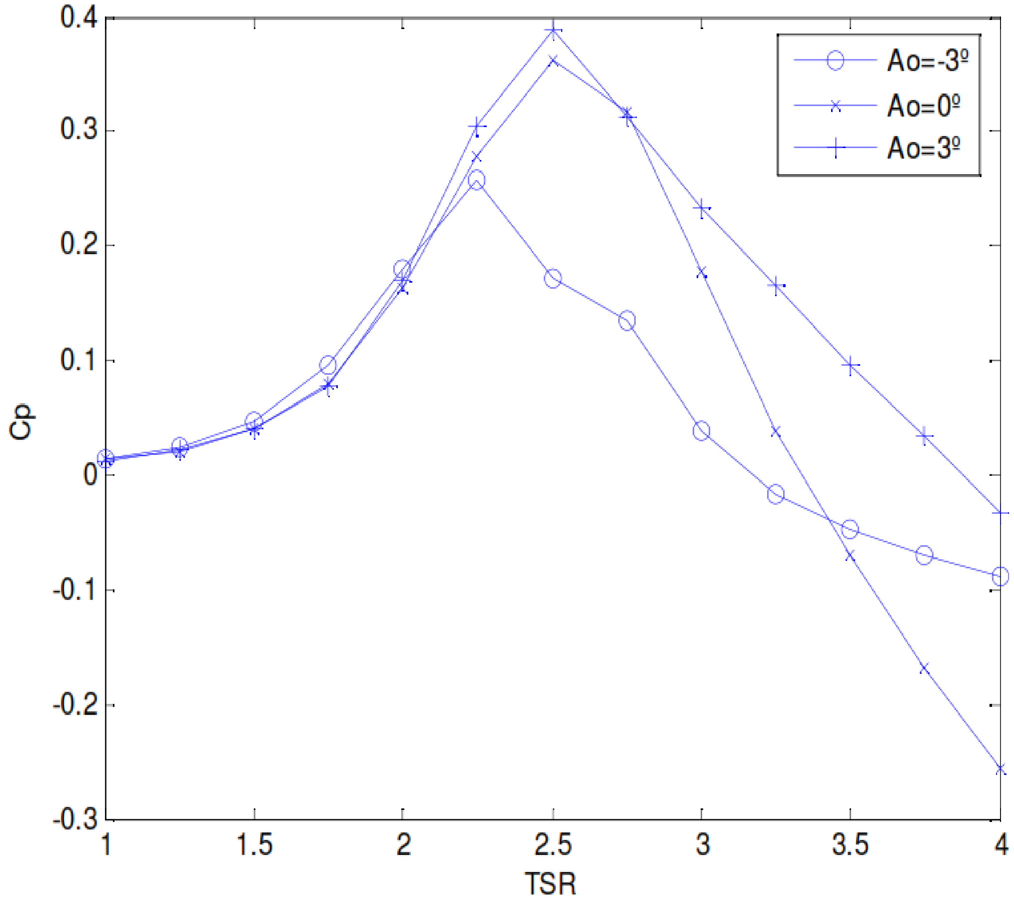


Figure 3.8: Power coefficient variation depending on the initial angle of attack.

3.1.13 Rotor Configuration

Three different rotor configurations (see figure 3-9) was considered and numbered from left to right in order to refer them further in the analysis. The first configuration attaches each blade by two points, which correspond to the Bessel points and minimize the maximum bending moment. These points are located at 20.7% of the blade length from each blade tip.

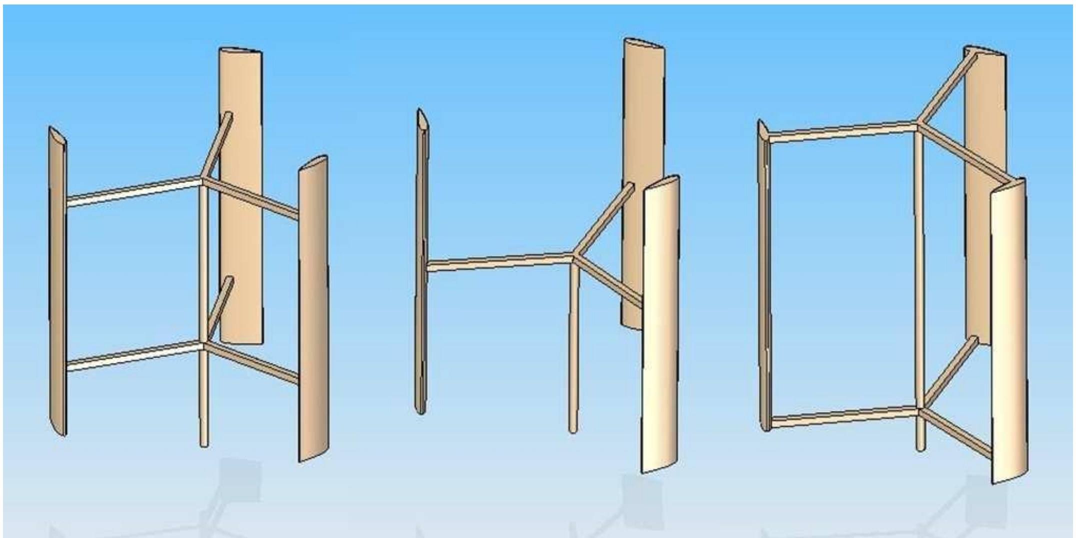


Figure 3.9: Rotor configuration

The first configuration was chosen while the second and third configuration were discarded mainly because in terms of maximum bending strength and shear strength they are equivalent, but the exposed area per same strength is low for both. This reduces the resulting drag associated with central mast and strut.

3.1.14 Final Prototype Design

With all the considerations arrived at in design modelling presented in chapter 3, the candidate for the fully optimized 500W wind turbine prototype is presented on table 4.4

Table 4.4: Chosen wind turbine sizing

Mean power output (W)	500
Number of blades	3
Radius (m)	1
Blade length (m)	1.6
Blade chord length (m)	0.2
Airfoil section NACA	NACA 0021
Fixed pitch angle (deg) +4	+4
Point of attachment	0.25 times the chord length
CP at TSR four	0.38

Using a procedure stated in (Manwell *et al.*, 2009) The power curve has been predicted graphically by matching the power output from the rotor as a function of wind and rotational speed and with their data make a Power output versus wind speed plot. A generator efficiency of 0.85 is assumed

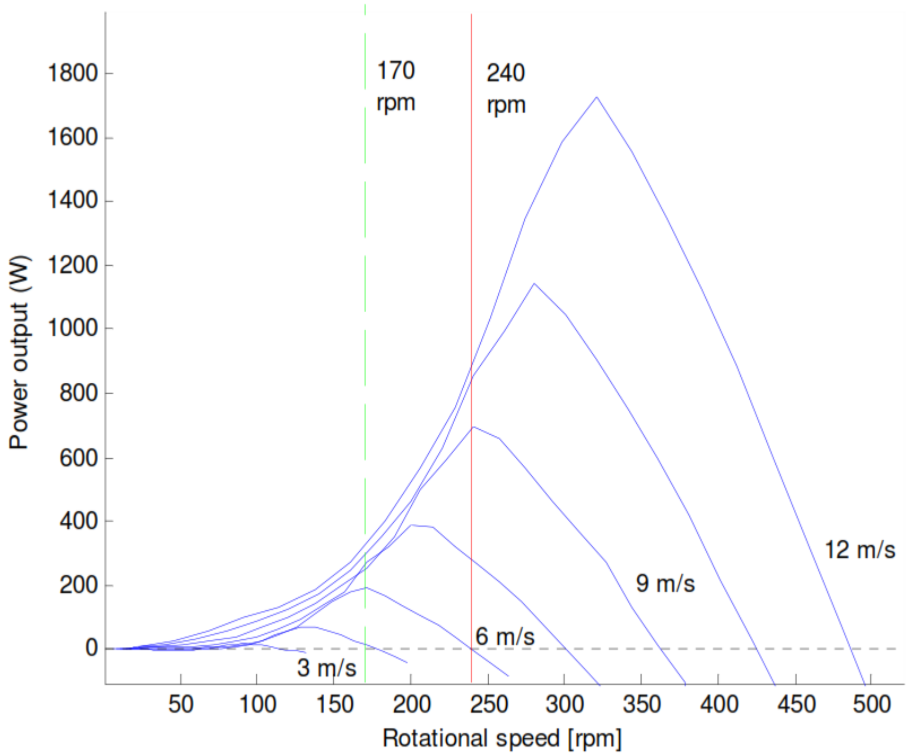


Figure 3.10: Power output at several rotational and wind speeds.

The rotor design gives (theoretically) 690 W at rated wind speed and the power obtained at 6 m/s at the same rotational speed is almost 0. However, power prediction curve will be made with field test data, as the generator specifications, algorithm inaccuracies and control system used play an important role on the shape of the power curve. The rotor torque curves at different rotational and wind speeds are presented on figure 3-11.

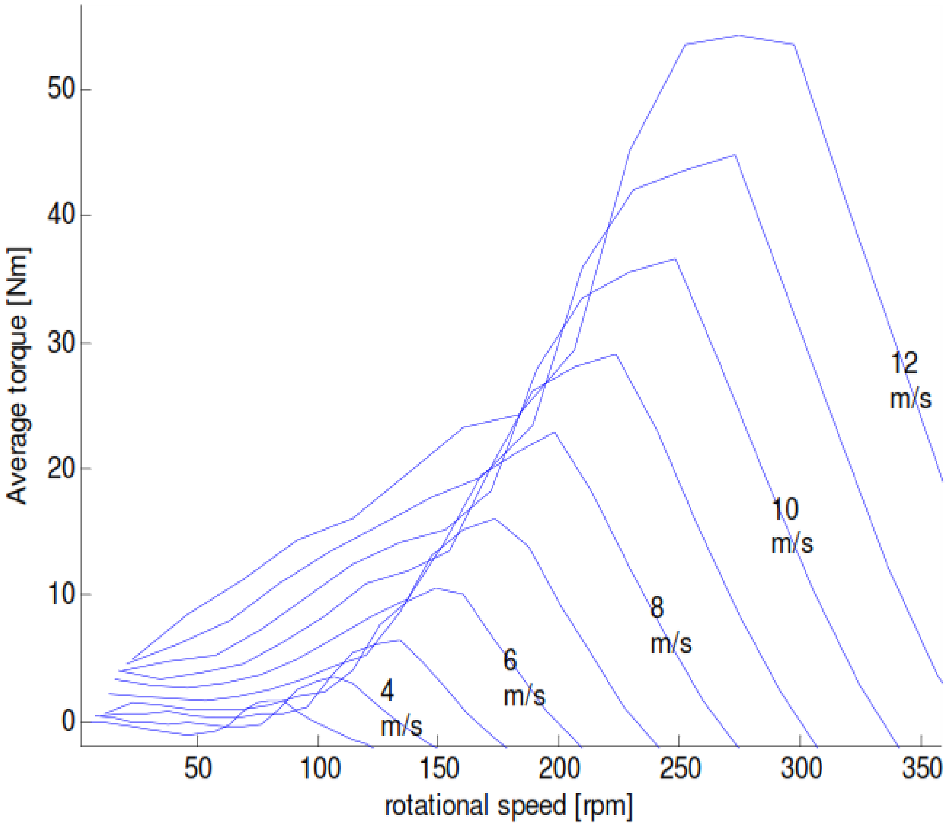


Figure 3.11: Average torque curves for several wind and rotational speeds

3.2 Fabrication of the Full Scale Turbine

Based on the final prototype design a full-scale turbine was constructed for experimental validation. This chapter outlines the materials and methods used in the construction before testing and data analysis.

3.2.1 Activities and Components

The components of the full-scale VAWT are listed below,

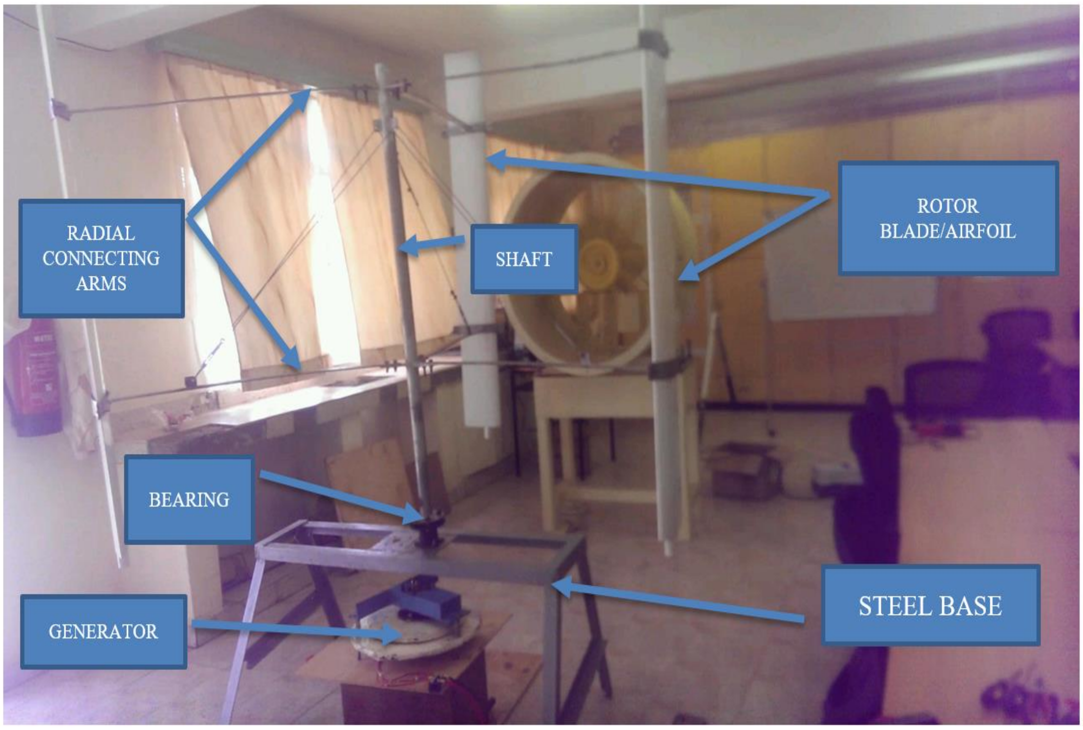


Figure 3.12: components of the full-scale VAWT

3.2.2 CAD Drawings and Blade airfoil

For this turbine design, all the parts were drawn by Autodesk Inventor. The AutoCAD drawings giving the details and dimensions of the wind turbine are shown in figures 4-1 to 4-3. These drawings were the blueprint used for production of the turbine

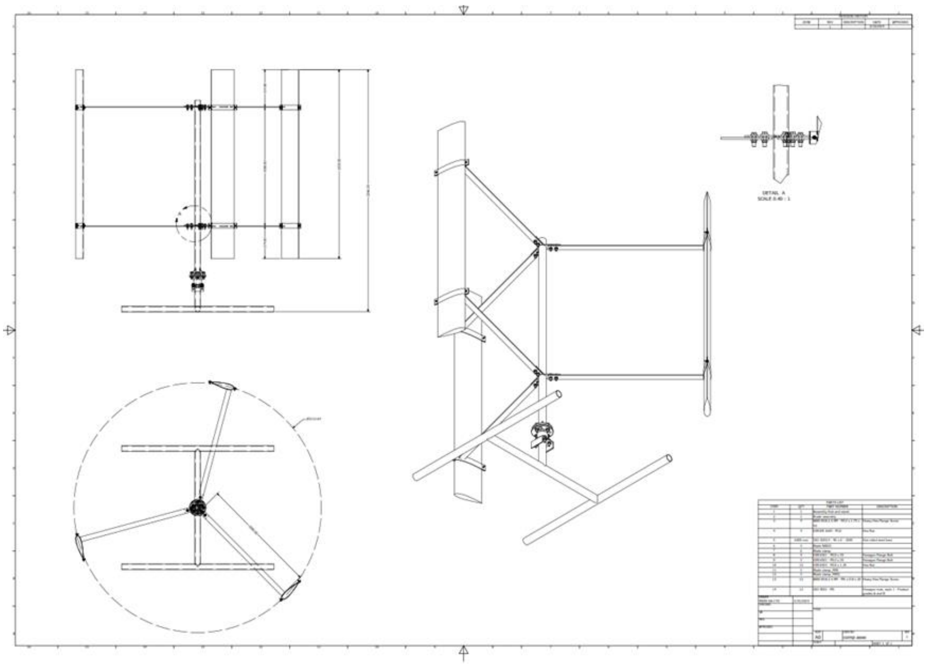


Figure 3.13: CAD drawing of the assembled VAWT

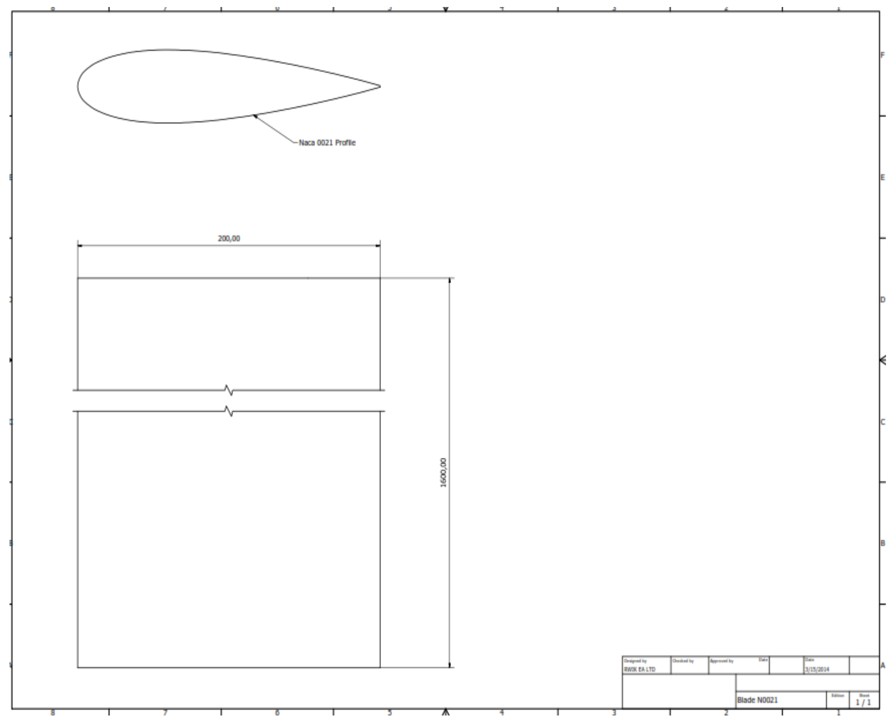


Figure 3.14: Blade drawing showing the dimensions

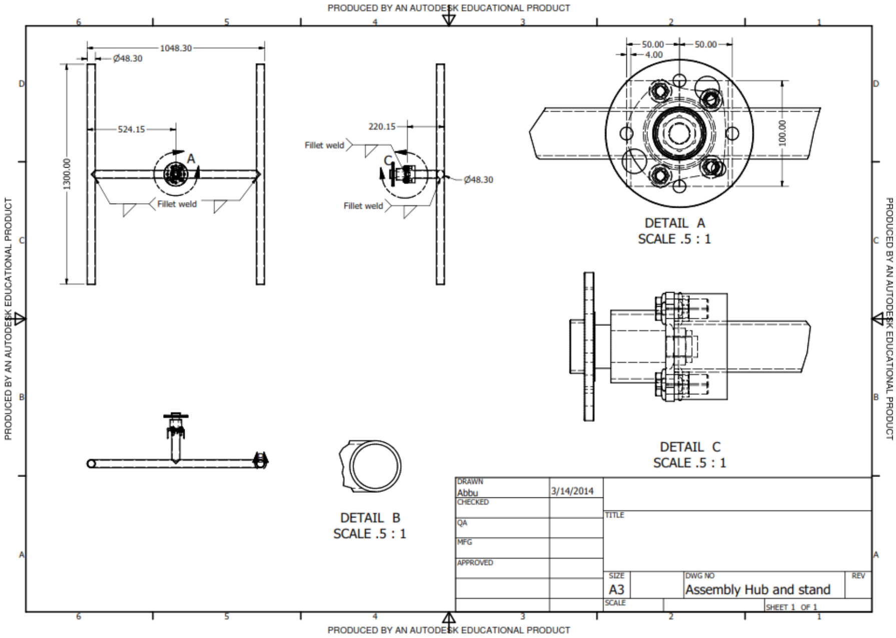


Figure3.15: Assembly drawing of the hub and stand

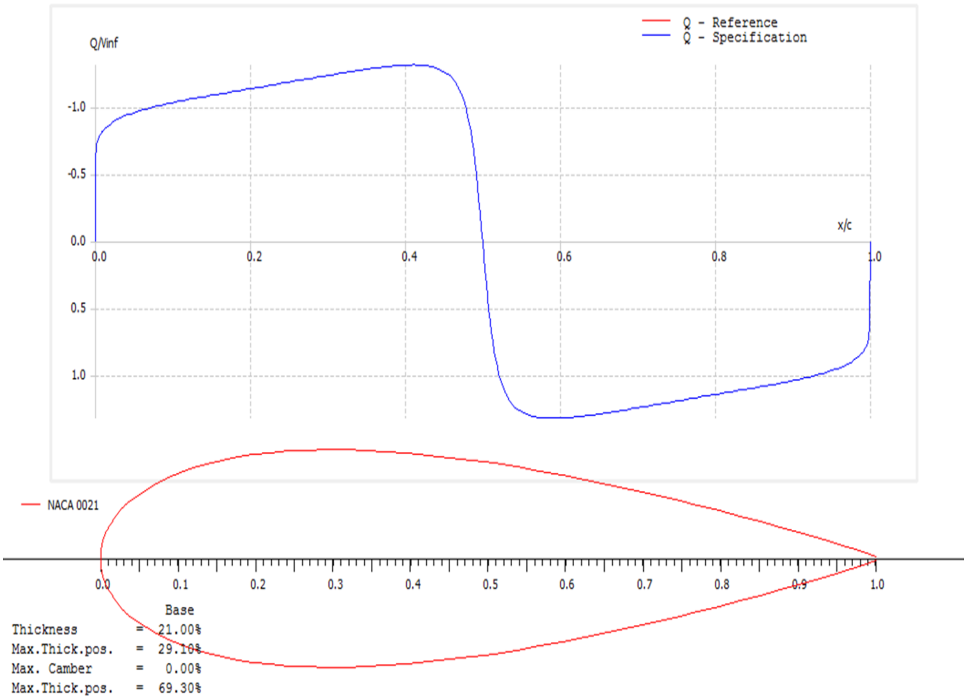


Figure 3.16: NACA 0021 Section Profile

Figure 3.17: Cut out NACA 0021 air foil profile

3 blades were machined from a wood into an accurate representation of the selected NACA 0021 airfoil specification. Figure 4-4. Figure 4-5 and figure 4-6 show the actual wood blade profile and NACA 0021 profile cut out.

Figure 3.18: Cut out profile that was used to align the wooden model

3.2.3 Steel Base

The base was steel and stands approximately 3 feet high. The base has to support the torque and moments produced from the wind turbine, so a base extension and a connecting bracket was included. The base acted as support frame that was necessary to house the rotor, bearings and the generator. The design criteria for the steel base was able to take the full weight of the rotor; withstand forces induced upon it from the wind; able to be disassembled, easy to handle; Provide for the mounting of the generator and able to withstand the elements of nature

3.2.4 Shaft

The design incorporated a 'live-shaft'. This means that the shaft rotates as part of the rotor. One of the main design aspects of the shaft was mainly for the assembly and disassembly purposes.

Galvanized steel was used because of its properties and benefits; first is it has the lowest first cost. Galvanizing is lower in first cost than many other commonly specified protective coatings for steel. It has less maintenance/Lowest long term cost. Even in cases where the initial cost of galvanizing is higher than alternative coatings, galvanizing is almost invariably cheapest in the long term (because it lasts longer and needs less maintenance). It has long life. The life expectancy of galvanized coatings is far in excess of 50 years in most rural environments, and 20 to 25 years plus, even in severe urban and coastal exposure. It has Reliability. Coating life and performance are reliable and predictable. It's got the toughest coating. A galvanized coating has a unique metallurgical structure which gives outstanding resistance to mechanical damage in transport, erection and service. Galvanised steel has an Automatic protection for damaged areas. Galvanized coatings corrode preferentially to steel, providing cathodic or sacrificial protection to small areas of steel exposed through damage. It provides complete protection. Every part of a galvanized article is protected even recesses, sharp corners and inaccessible areas. A full protective coating can be applied in minutes; The galvanizing process is not dependent on weather conditions

3.2.5 Bearings

Minimizing required start-up torque is essential for the wind turbine to self-start. Without proper bearing the turbine will either not operate properly, or ruin the bearings if used improperly, which could result in unsafe operating conditions. Bearings can be very expensive, and for the project a car herb roller bearing was used to primarily centralize the shaft. This type of bearing provided the least amount of friction, size, and weight, while maximizing bearing life, carrying capacity and durability as well as maintaining safe operating conditions.

Figure 3.19: Car hub bearing used

3.2.6 Connecting arms

Flat iron bars were used for the six radial connecting arms to maintain a lightweight assembly with minimal inertial, moment, and centrifugal forces. The connecting arms provide a means to mount the blades to the centre mounts and thus the centre shaft.

Figure 3.20: A picture of the shaft, connecting arms and blade.

3.2.7 Tooling

The tools used were; Pliers, Hammer, Hand drill and bits Compass (for marking wood with half circles), Sharp permanent marker, Goggles, Clamps , Drill guide for making perfectly perpendicular holes in centre of wood rounds, Pencil, Skill Saw for cutting miscellaneous wood for platform, Tape measure 0-30m, Gloves, Syringes (or pipettes), Pots and mixing sticks, Scales, Paint brushes, Scissors, Marker pens, Rags/cloths, Sandpaper, Power grinder with cutting disk and sanding disk and Mixing tools and spatulas for car body filler

3.2.8 Selected Rotor Blade Material

GRFP (glass reinforced Fibre plastic) was the chosen material for rotor blades because of following favourable properties;

3.2.8.1 Freedom of Design

GFRP has unique physical properties which allow it to be easily tooled, moulded and manufactured to meet almost any specifications. With GRFP there are few constraints on size, shape, colour or finish, the styling and appearance can take precedence over manufacturing costs (WebServices, W. C. (n.d.).

3.2.8.2 Versatility and Affordability

The lightweight strength of GRFP makes it a popular choice for manufacturing. GRFP reduces weight and requires less maintenance making it highly attractive over more traditional materials like timber, metal or brick (WebServices, W. C. (n.d.).

The flexibility of GRFP and the cost effectiveness of its composite materials also make it an extremely affordable solution and an economical alternative. By using GRFP any component can be manufactured or finished in any quantity (WebServices, W. C. (n.d.).

3.2.8.3 Strength and Durability

GRFP has a high strength to weight ratio and high flexural strength making it an attractive lightweight material that builds strength into almost any finished product or component.

GRFP also has high resistance to environmental extremes and requires very little maintenance - no rust, no painting, no wood rot plus GRP is non-corrosive and has a much longer life expectancy when compared to a variety of construction materials (WebServices, W. C. (n.d.).

In highly corrosive environments GRP is the preferred choice over metal, wood, or plastic. GRP provides resistance to ultra violet light, extreme temperatures, salt air, and a variety of chemicals including most acids. As GRP is chemically inert and corrosion-resistant, it offers an economical alternative to stainless steel (WebServices, W. C. (n.d.).

3.2.8.4 Appearance

GRP products can be manufactured in numerous finishes, textures and colours. With sheet metal, you get a plain box. GRP products have sleek contours and a superior moulded appearance (WebServices, W. C. (n.d.).

3.2.8.5 Dielectric

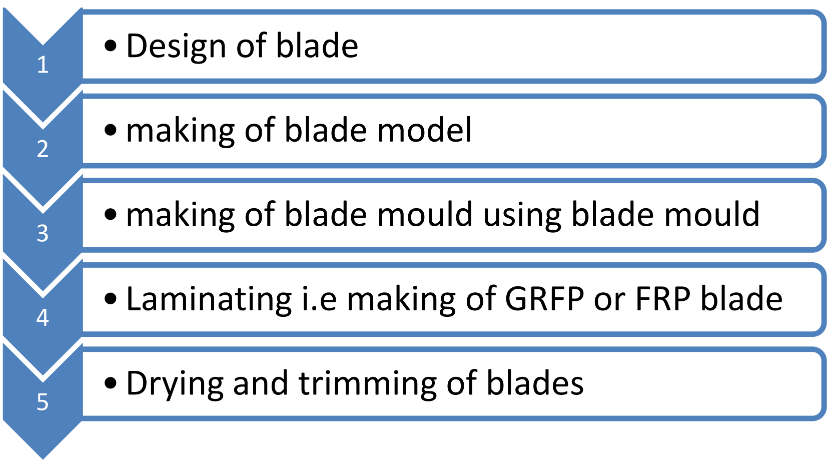
GRFP is non-conductive, RF transparent, and helps to insulate against electromagnetic fields. This property makes the designer eliminate the lightening protection design (WebServices, W. C. (n.d.).

3.2.8.6 Acoustic Properties

GRFP provides superior acoustical properties when compared to plastic or metal. Various type of sound deadening materials can be laminated between high strength layers of GRP to achieve the preferred level of sound deadening. GRFP parts have excellent dimensional stability and will hold their shapes under severe mechanical and environmental stresses.

3.2.9 GFRP Rotor Blade Production

The manufacture of the GRFP rotor blade was done through a sequence of steps as detailed below.



From the numerical design process parameters wooden model as shown in figure 4-6 was produced for use in making GFRP blade copies. The first process was to do the Moulding, followed by lamination. The moulding was polished by use of wax so as to prevent the lamination from sticking to it. The wax forms a cushion whereby the laminate rests and remains independent of the moulding. A paste of the required colour was then poured over the wax which is mixed with a hardener and a catalyst to speed up the process of solidifying. Then fibre glass matt was placed whereby the desired thickness determines the number of Matts to be used; this was done in conjunction with the application of resin which acts as the bonding agent. Immediately laminating was over, a hardener and a catalyst was added to speed up the drying process. However, this was a sensitive stage because it is essentially controlled by the given Locational environmental conditions. It is preferable the fibre glass production is undertaken in an open atmosphere. If the weather is hot it dries out quickly, if on the contrary it is cold, it may take longer. On normal average weather conditions, the process may take two to three days for the chemicals to dry and the curing process to complete. After drying; a moulding releasing agent is used to separate the moulding from the laminate (final product) and undesired protrusions are trimmed off. The product is then ground to give it a smooth finish. If there are any cracks due to contractions and expansions in response to weathering, a filler is used to repair and, where there is a visible rough surface, a layer of paste is applied to smoothen it mixed with monomer to make it non-sticky. If there are un-coloured spots, they are painted to give a uniform elegant finish. The first trial was done at a Local Jua kali glass fibre workshop. figure 4-9 shows the process and outcome. A single product / prototype was produced.

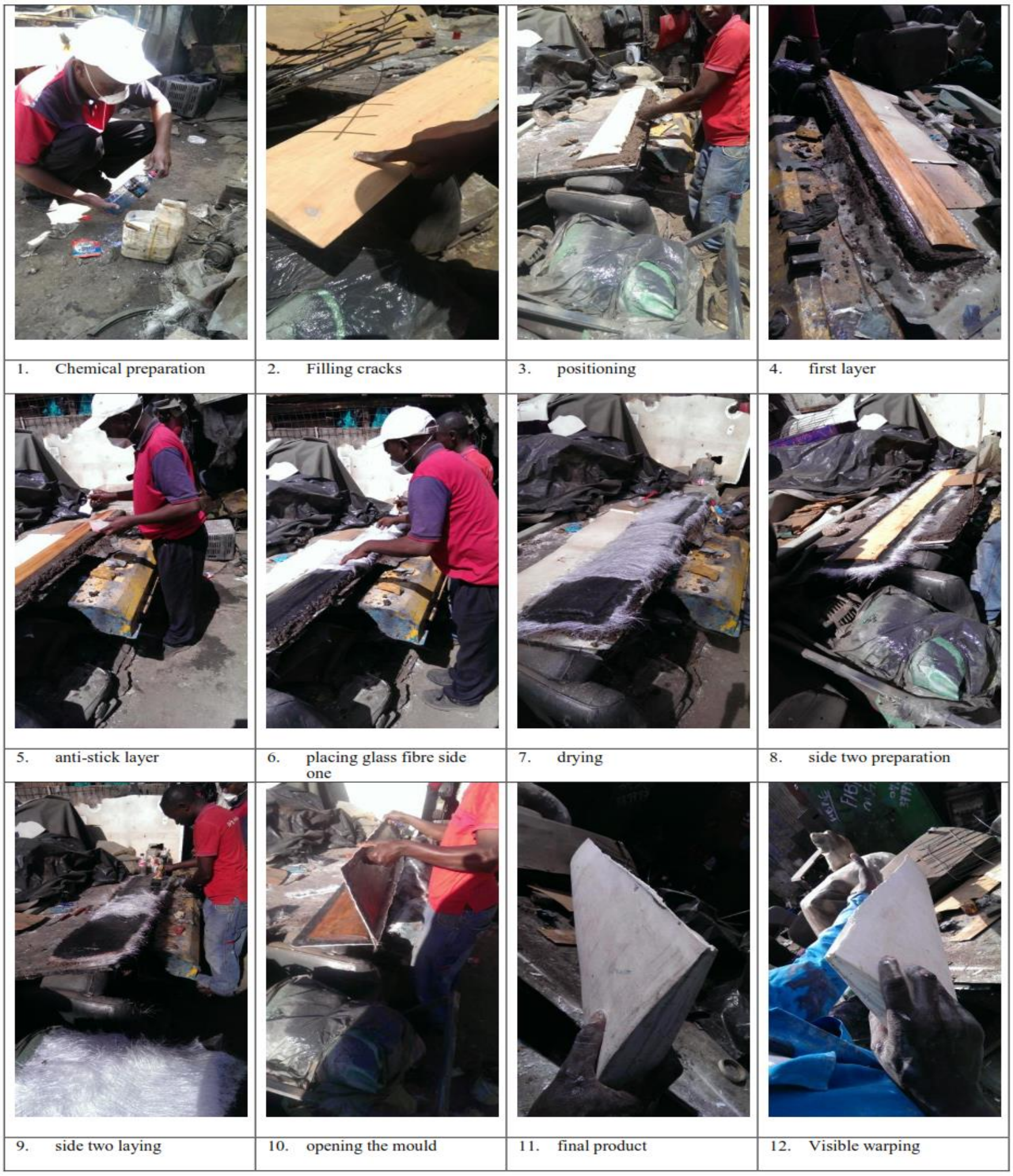


Figure 3.21: Blade production process at a Jua Kali artisan workshop

The final result was a warped blade. A second attempt was carried out at Sai Raj workshop because of their ability to produce complex, multi piece production moulds with high quality finishes. By controlling critical dimensions and shape a properly manufactured and structurally supported mould was created, equally important is the type and quality of materials employed during mould construction. Figure shows the blade production process at Sai Raj workshop.

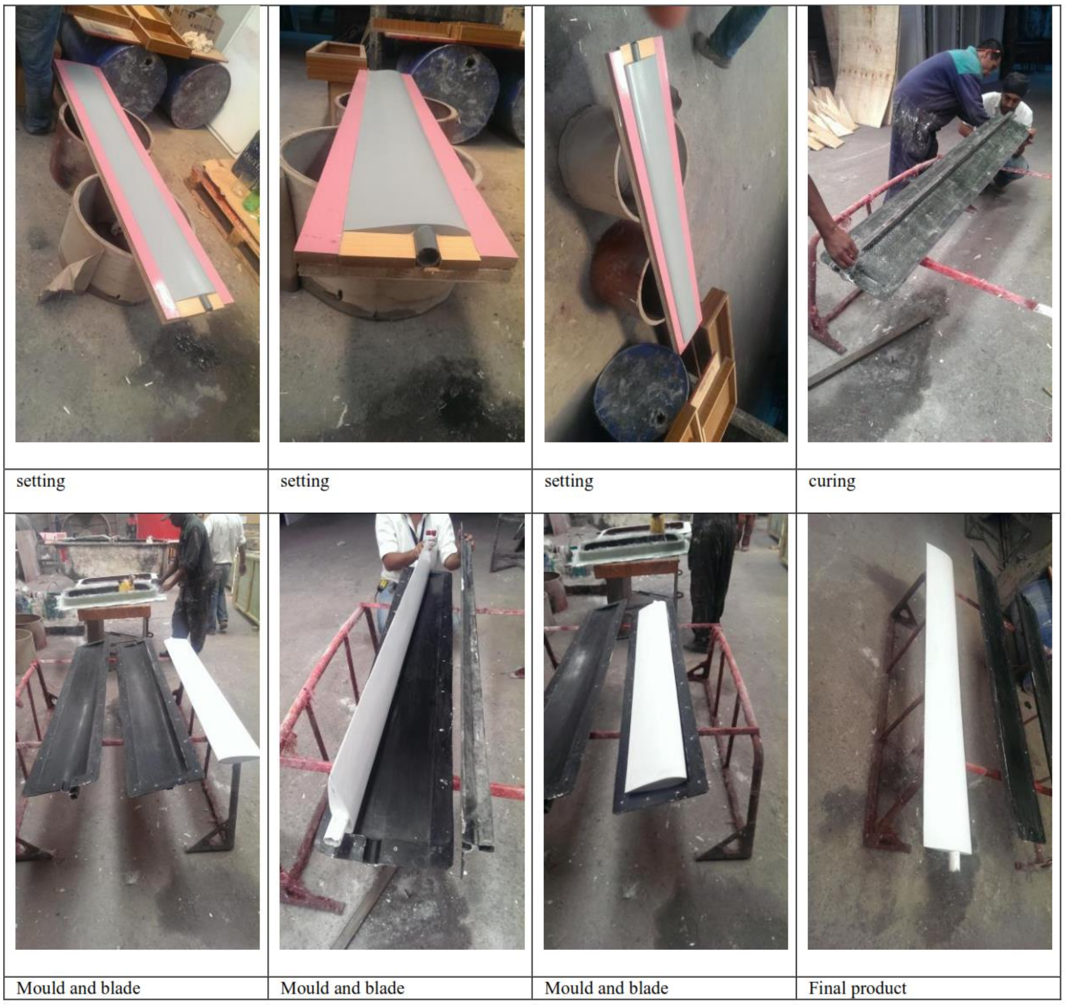


Figure 3.22: Blade production process at a Sai Raj workshop

3.2.10 Structural Analysis

A structural analysis was carried out to provide the limits of operation of the turbine, in terms of rotational speed, in order to prevent structural failure. The analysis was done by doing a configuration of the wind structure and the maximum bending moment, normal and shear loads on a blade. Obtaining the ultimate stress modules were checked by consulting tables of mechanical properties of materials and by calculating the safety factor to check the allowable stresses and loads. The numeric values of the allowable loads are calculated and a check is done to see if the turbine is able to accelerate to a point where the structural allowable limits can be surpassed (Gere, 2004).

3.2.11 Generator

Since the wind turbine was connected to the generator developed by (Akello *et al,*. 2014), it is prudent to give some specifications of the generator. The make is the Permanent Magnet Axial Flux (PMAF) generator, a type of permanent magnet generator (PMG), which uses permanent magnets, and is based on the fact that a changing magnetic field through a copper wire will induce a flux or electrical current (Bartmann & Fink, 2009). This PMG configuration is the most widely used technology for SWTs below 2 KW, since they start producing power in low winds and at relatively high efficiency (Berges, 2007). Other advantages are its simplicity and accessibility, and the fact that it can be made of basic materials (Dunnett, *et al.*, 2001). The researchers developed the generator consisting of two rotor discs mounted either side of a nonmagnetic, on conducting stator as illustrated in figure 4-11 (Ani, 2013). The generator parameters and calculated dimensions are shown in table 3.5. To measure the efficiency of the generator, a test set-up consisting of a Variable Speed Drive (VSD) controlled the power to a 3-phase motor. The motor was used as the prime mover emulating the mechanical characteristics of a wind turbine as shown in figure 4-12.

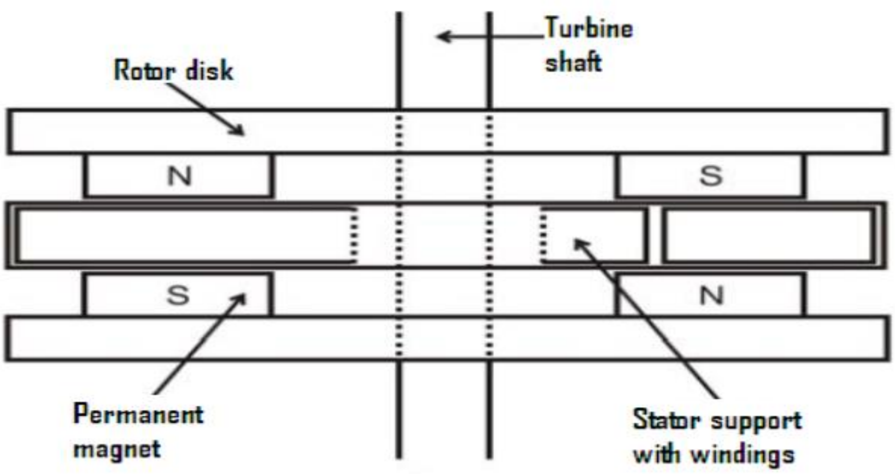


Figure 3.23: The double-rotor axial flux generator with air cored stator

Table 3.5: Generator main parameters

Symbol	Quantity	Value
P_{out}	Output Power	1 KW
N	Rated Speed	250 RPM
V	Output voltage	24 V
P	Number of pole pairs	12
Φ	Phase number	3
r_i	Inner rotor disk radius	129 mm
r_o	Outer rotor disk radius	175 mm
D_r	Rotor Diameter	350 mm
r_{si}	Inner stator radius	129 mm
r_{so}	Outer stator radius	240 mm
t_s	Stator thickness	10 mm

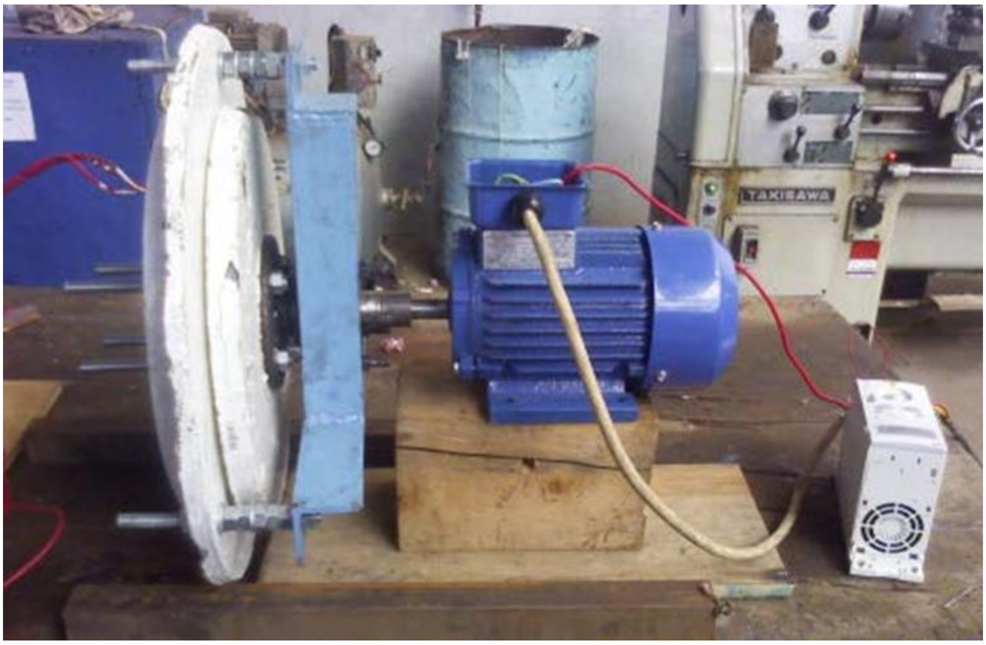


Figure 3.24: The generator set up

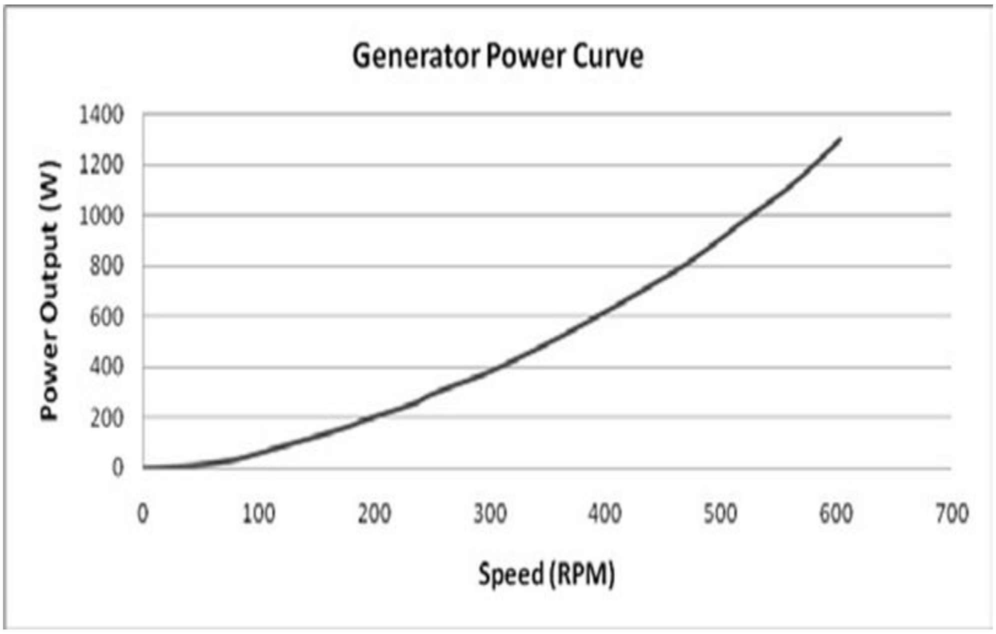


Figure 3.25: Generator power curve Performance Test

CHAPTER FOUR

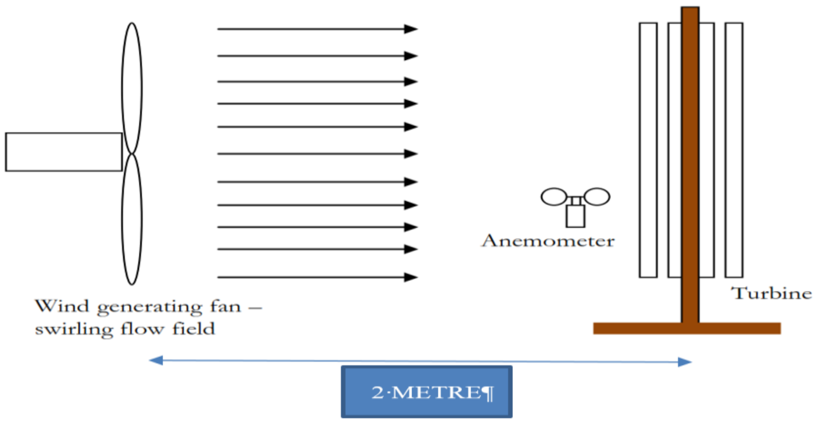
RESULTS AND DISCUSSION

4.1 Introduction

As discussed in chapter 3 a full scale turbine was constructed for testing. During the period of this study it was hard to find and access a wind site with considerable wind speed. Therefore, it was decided to use artificially generated wind speeds to test the wind turbine. With the limited resources available to the project, performance monitoring and testing were carried out by applying wind forces to the turbine in by use of a large industrial fan to generate required wind speeds, resembling a wind tunnel setup and the variable motor acted as speed regulator to set different wind speeds.

4.1.1 Experimental Set Up

The turbine was tested similar to a wind tunnel condition by applying wind generated from a large electric motor-driven fan operating at variable rotational speeds. The maximum output power from the turbine is usually obtained by controlling the system such that the relevant points of wind rotor torque and break load operating characteristic coincide. The testing set up was as shown in figures 4-1 to figure 4-3.



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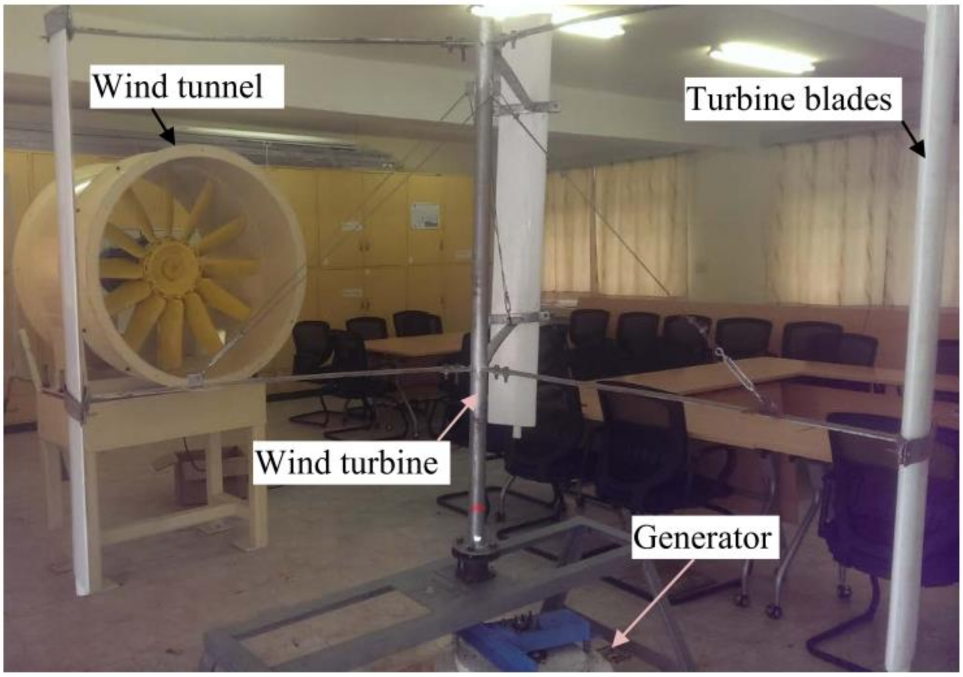

Figure 4.1: The turbine performance test set up.

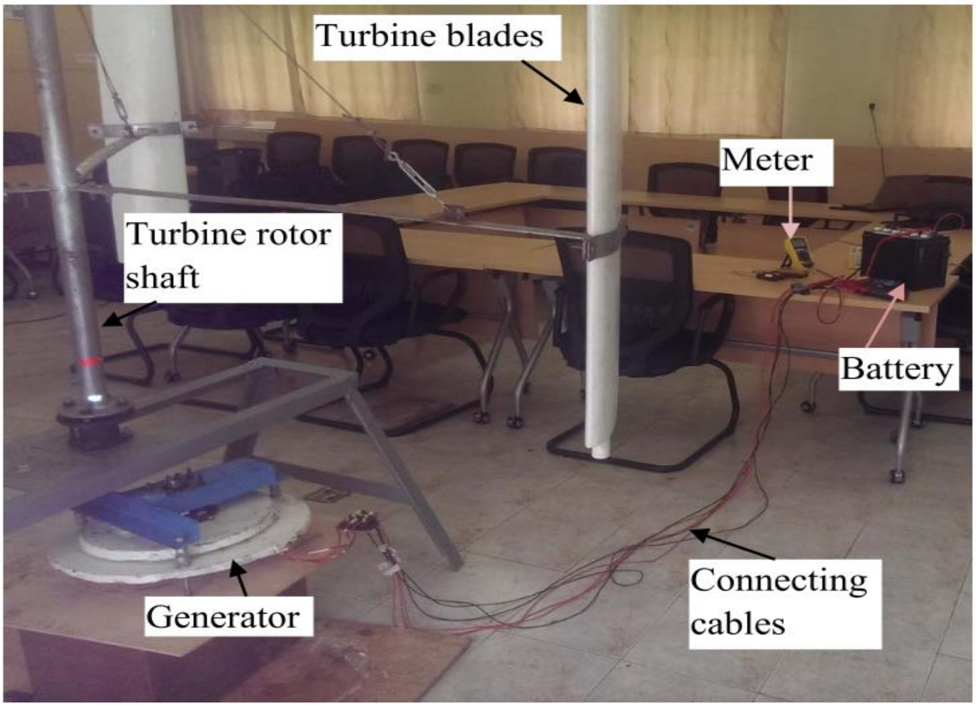

Figure 4.2: The performance test set up showing charging system

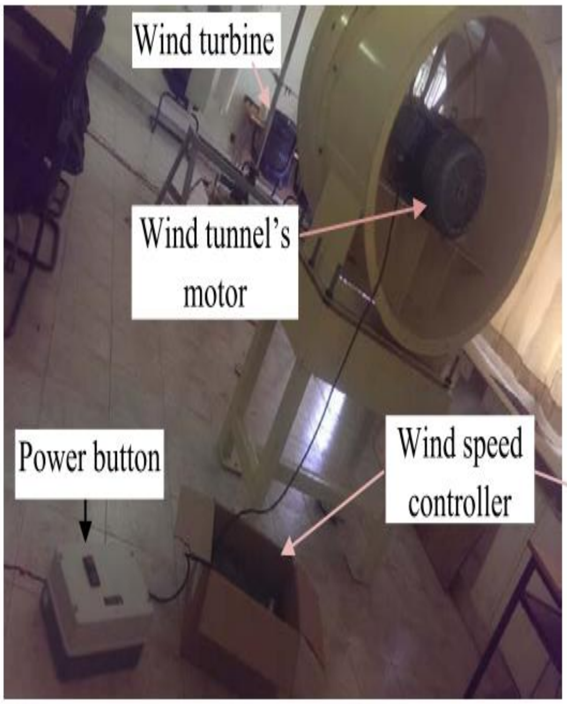

Figure 4.3: Performance testing set up showing the fan and variable speed drive

Main drawback of using a fan as a wind Generator is the wake and swirl generated by fan rotation. Therefore, it is vital to minimize the effect of swirl by placing the turbine at some distance to the fan. In this experiment the turbine was kept at a distance of 2m away from the fan. This distance was selected by practical means, for example by observing and minimising the magnitude of anemometer reading variations.

In this experimental setup, wind velocity was measured by a digital anemometer. The anemometer was fixed near to the turbine rotor and it captures only the horizontal component of the wind velocity. Despite the imperfect conditions and possible deviations of wind speed, this experimental method was successful for the purposes of this study.

Most fluctuations and swirl effects were possible to eliminate by averaging and filtering the collected measurement data

4.1.2 Observation

The wind turbine was connected to a generator produced by (Akello *et al.,* 2014) and the performance were measured at different wind speeds. Various speeds were used and the power output from the generator was measured using a power meter. Further, at the various set speeds, the static torque and rotational speeds were measured using a static torque meter and tachometer respectively.

As shown in section 3.2.11 of this report figure 4-14 the generator developed by (Akello *et al.,* 2014) produced power at rated RPM of 280 RPM, was 293W as shown in the power curve in efficiency under the rated speed was 29.3%. The generator, during testing, produced power beyond the rated 1 KW at much higher speeds.

During the experimental validation, the speed of the wind was changed by varying the rotational speed of the motor using the wind speed controller. The rotational speed of the wind turbine was simultaneously measured using the digital tachometers shown in figure 5-4. It was observed that at a wind speed of 14 m/s the turbine gave the highest power of 190 W at 280 RPM, 12 m/s gave the highest power as 156 W at 230 RPM, 10 m/s gave the highest power as 120W at 180 RPM while 8 m/s gave the highest power as 96 W at 140 RPM. 250 is the rated RPM for the Generator. The turbine torque was 1.56Nm at an RPM of 175.

Figure 4.4: The digital tachometers.

Table 4. 1: Power at different wind speeds and RPM

Wind speed (m/s)	**Power (W)**	**RPM**	**Cp**
6	50	118	0.02
8	96	140	0.03
10	120	180	0.04
12	156	230	0.05
14	190	280	0.09
16	170	290	0.11

The power coefficient C of the wind turbine was used as primary parameter for the performance analysis. Definition of Cp is given below.

$$\boldsymbol{C\rho = \frac{P}{\frac{1}{2}\rho u^3{}_{wind}A}} \quad \textbf{... 16}$$

where P is the power produced by the turbine and A is the area swept by the turbine rotor. This coefficient is a function of the tip speed ratio , t $\lambda = U_{blade}/U_{wind}$ where for an H-type Darrieus turbine, this parameter is constant over the entire blade. Figure 5-5 shows the power curves of Cp for all tested wind speeds. The curves suggest that the dimensional power performance of the turbine can be reliably predicted from the Cp curve for all rotary speeds and for all wind speeds between 8 and 16 m/s. The maximum power coefficient occurs at TSR of 4, reaches a value close to 0.1.

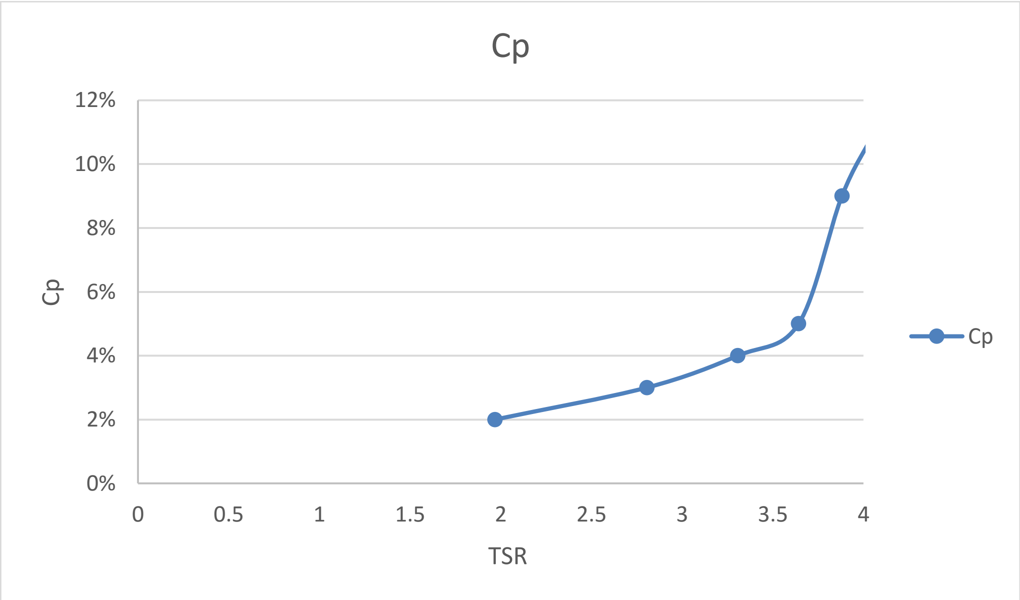

Figure 4.5: Variation of CP vs TSR

The maximum efficiency recorded was 11%. The power coefficient curves for the different wind speeds are as shown in the figure 5-5. These power curves are very instrumental in assessing the performance of a turbine to capture wind energy. From theory, it is known that the tip speed ratio of a turbine helps to maximize the power output and efficiency of the wind turbine in that if a rotor spins too slowly, a lot of wind will pass through the gaps between the blades rather than giving energy to the turbine. Also if the blades spin too quickly, they could create too much turbulent air or act as a solid wall against the wind. So, the Tip Speed Ratio is helpful in maximizing the turbine's efficiency

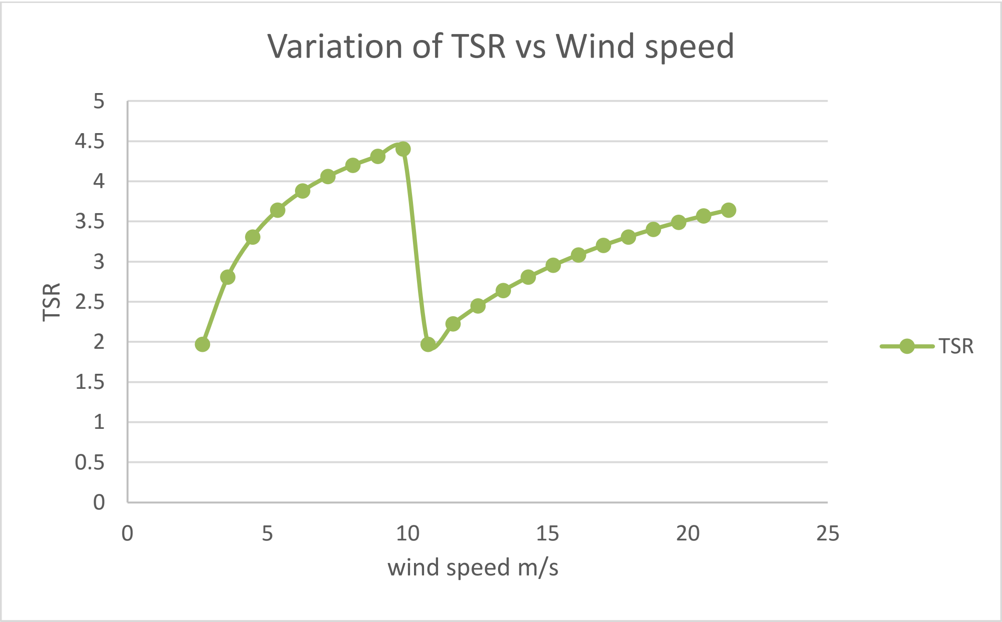

Figure 4.6: Variation of TSR vs Wind speed

Tip speed ratios versus wind velocity for the rotors are shown in Figs. 5-6, the related mean of tip speed ratios was initialized as 4 m/s or 5 m/s, and then increased by steps of 0.5 m/s up to the maximum observed speed. it was clear that rotor has the highest tip speed ratio at wind speed of about 9m/s and then drop to about 2. This can be attributed to turbulence generated from the industrial fan.

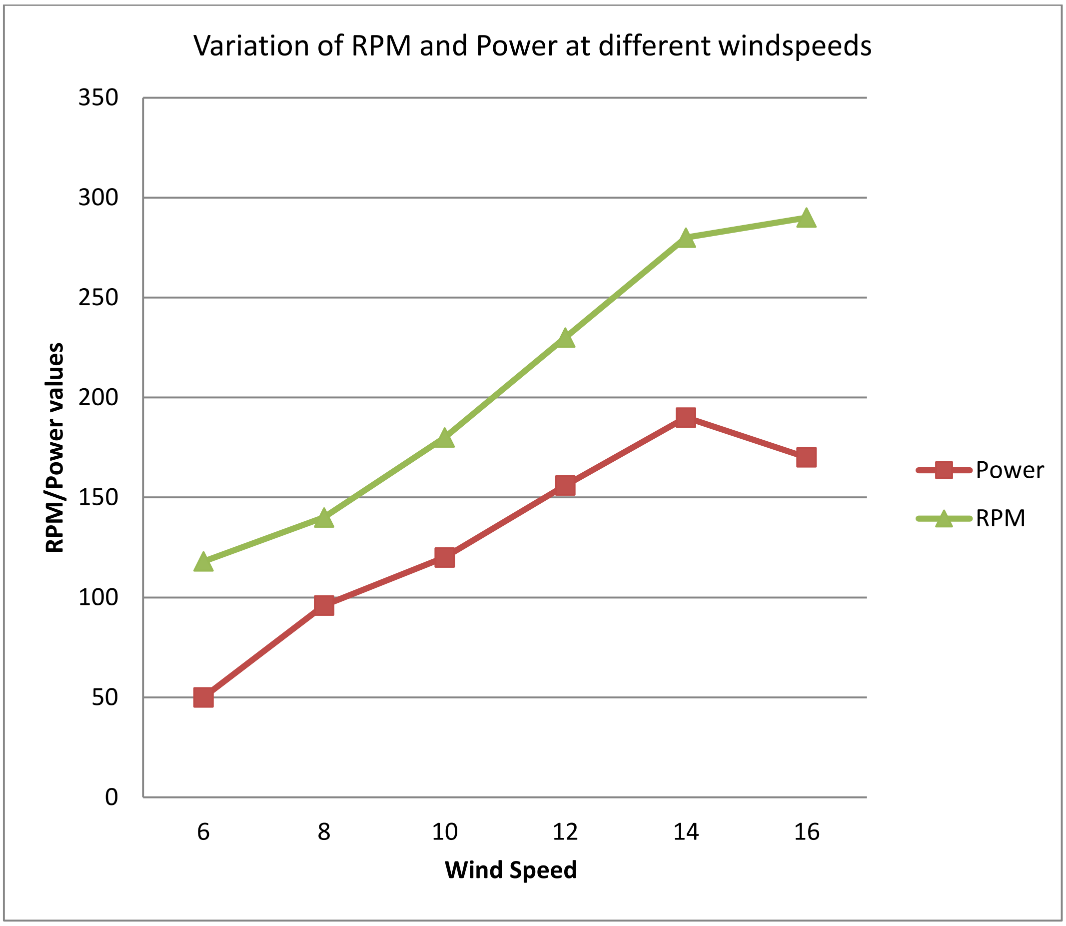

Figure 4.7: Variation of RPM and Power at different wind speeds

The resulting power curves are shown in Fig.5-6. The rotor at 14m/s produces the highest power at high RPM (over 250), while the rotor at rated wind speed of 6m/s produces the lowest power overall.

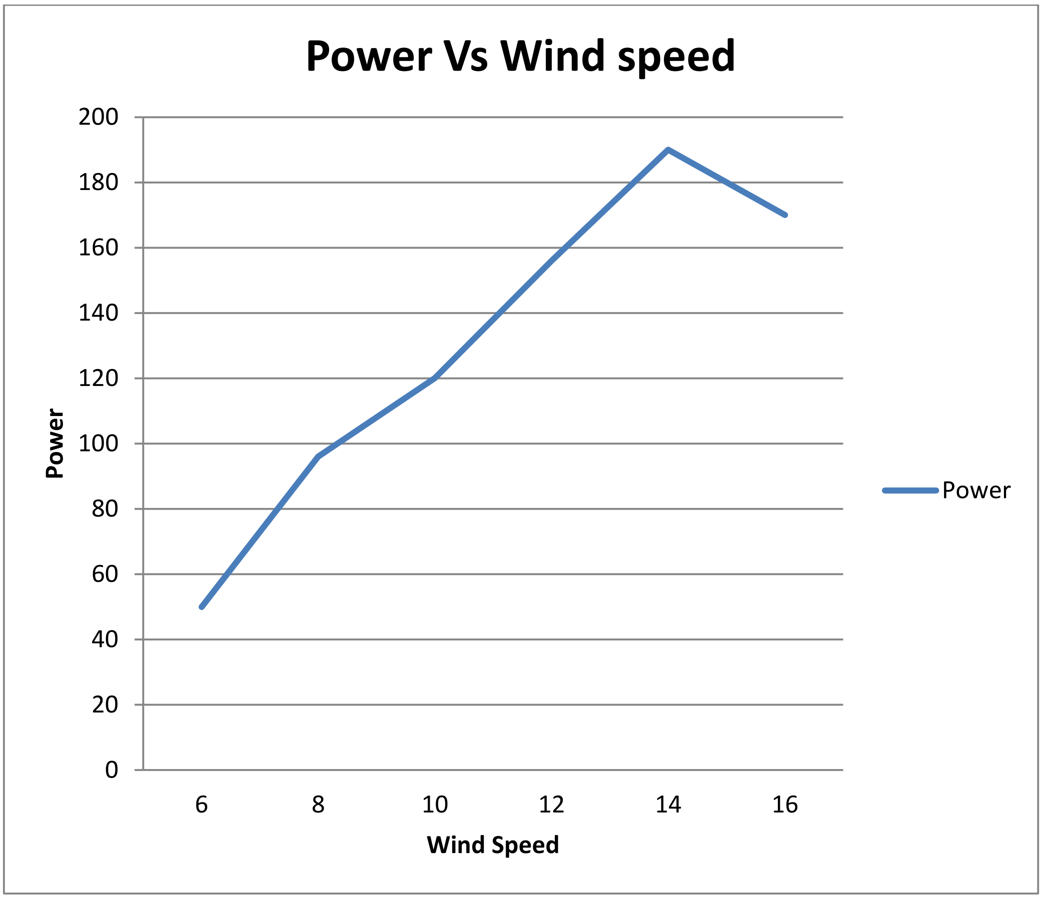

Figure 4.8: Power output Vs wind speed

Fig.4-7 shows that the rotor has a very low maximum power output of less than 60 W. at rated wind speed. Further calculation found that most tip speed ratios are less than 3. It is believed the low performance is due the turbine using a high speed generator.

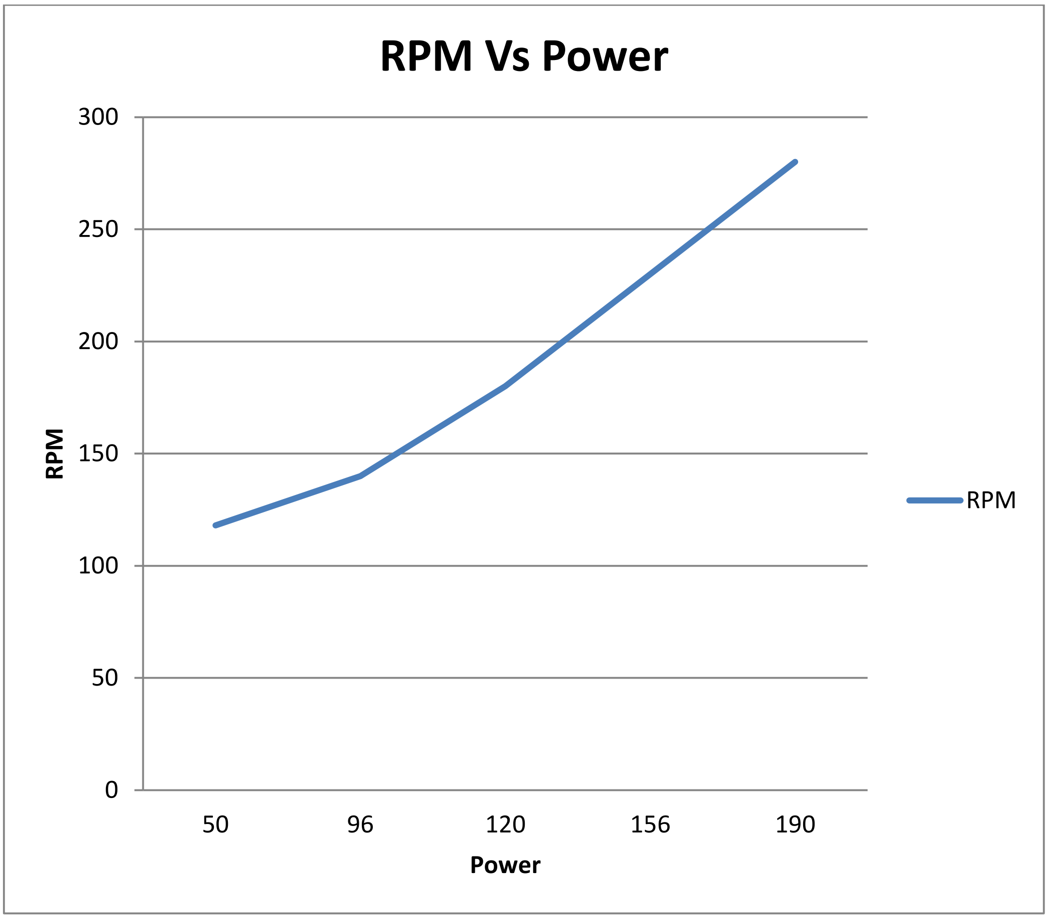

Figure 4.9: RPM vs. Power

The turbine generator is a permanent magnet alternator that is directly connected to the rotor shaft. Using a 2.01 Ω resistor as the electrical load means the electrical load is very consistent during turbine operation. The power output of the turbine would therefore be expected to be a consistent function of shaft rotation speed. The data from the rotors tested were combined to produce the plot of power versus rotation speed shown in Fig.4-8. This data confirmed that there is a fixed relationship (the fitted equation) between power and rotor speed in this test, which further proved the test data are consistent

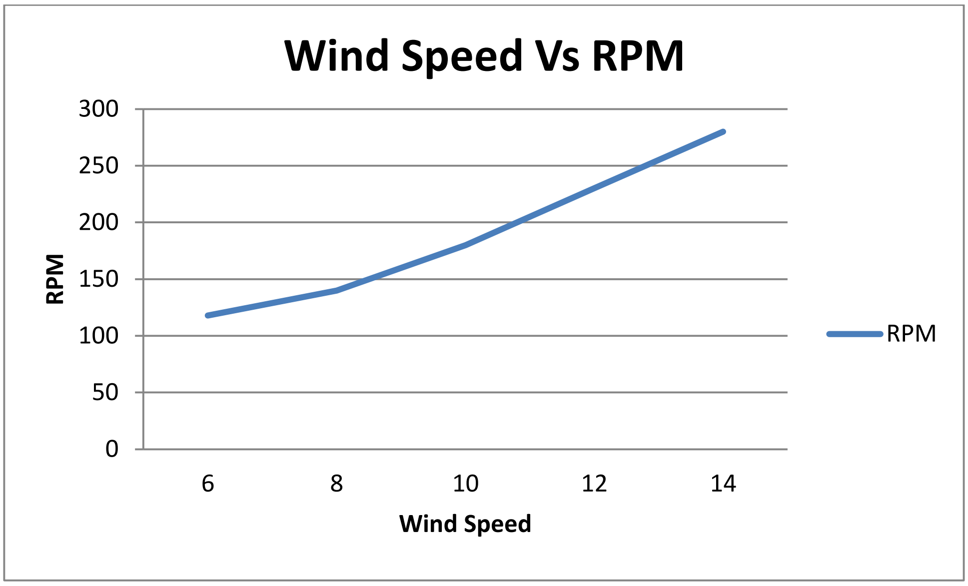

Figure 4.10: Wind Speed Vs RPM

As shown in figure 4-10 the rotor speed as a function of wind velocity, was relatively consistent with power versus wind velocity.

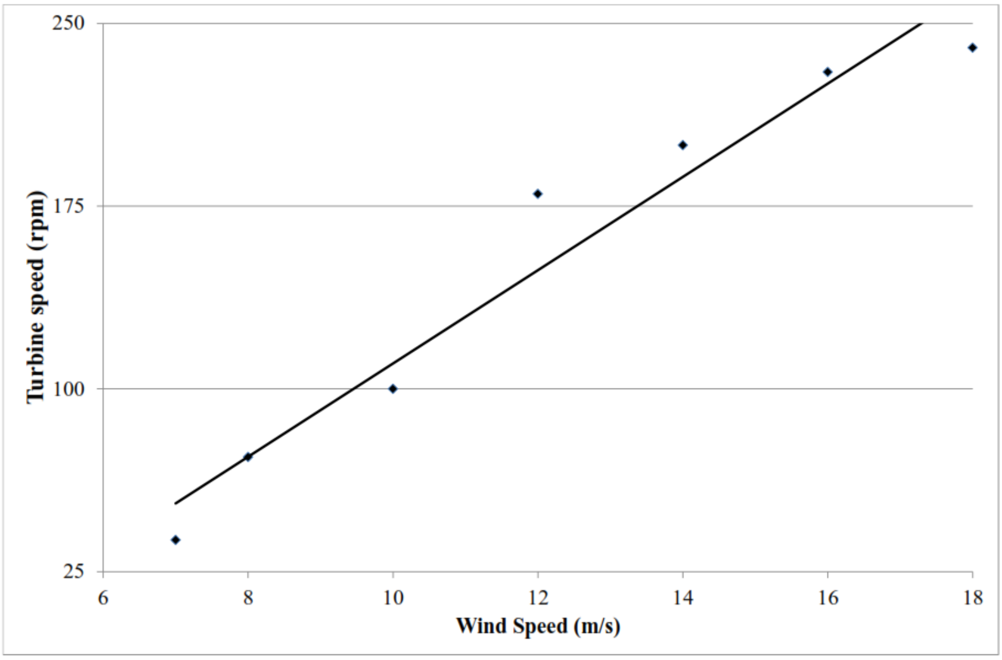

Figure 4.11: Variation of the turbine rotational speed with the wind speed.

Figure 4-11 shows the curve for the rotational speed (RPM) of the turbine against the wind speed. This curve shows that the rotational speed of the turbine has a linear relationship with the prevailing wind speed. Figure 4-12 shows the torque versus the turbine rotational speed curve. This result agrees with the equation **Error! Reference source not found.** that guides the power output from a wind turbine.

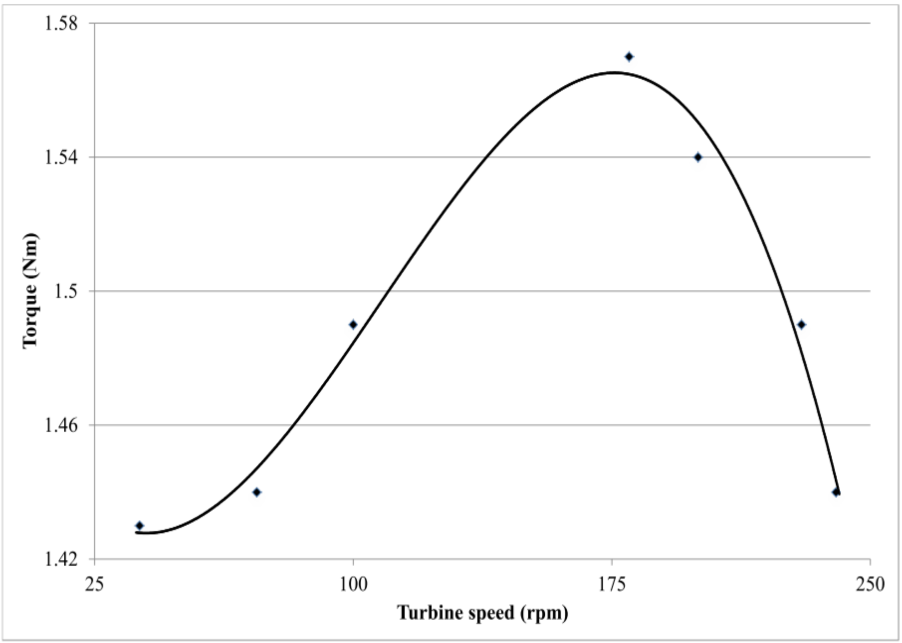

Figure 4.12: Torque versus turbine rotational speed curve.

From the graphs, it can be seen that the wind turbine is relatively efficient and with the right generator, it was capable of producing sufficient power. However, the efficiency of the turbine could not be quantified. The turbine also produced a maximum torque of 1.57 Nm at a rotational speed of 180 RPM. This was at a wind speed of 12 m/s. Qualitatively, the turbine took a very long time to increase rotation speed, and during testing it rarely operated at designed tip speed ratio. There was a balance between power and lowest working wind speed (around 40 W output). It was also noted the blades needed higher wind speed. audible noise from the blades was only noted a few times, at the highest wind speeds.

4.2 Viability of the VAWT

It is crucial to evaluate the availability of wind before installing a wind system since only then one can judge on its viability to generate power at a certain location. For this reason, wind data is one of the most essential pieces of information for the dissemination of SWTs in Kenya (Osawa, *et al.*, 2004).

The economic viability of wind systems at a certain wind speed largely depends on the wind system cost and its envisioned application. Whereas some small wind turbines are commercially attractive from average wind speeds from 4 m/s, some only become viable at wind speeds from 7-8m/s (Dunnett, *et al*., 2009).

Besides that, wind data is also required for the design and sizing of a small wind turbine for a specific location. For these purposes, one must have more data than only average wind speeds. The wind speed distribution, variation of the wind speed during the year and variation of the wind speed during the day are other parameters needed to select the right wind system and battery size (Manwell, *et al*., 2002).

It must be noted that wind speeds may greatly vary within the same area or locality. They are for example heavily affected by its surroundings. Trees, buildings and other structures impart turbulence in the air, which in turn lowers the turbine output and increases the stresses on the wind system. The prevailing wind direction is for this reason another important parameter to take into account, since wind turbines are best placed upwind of these nearby structures. Mounting a turbine on a roof also downgrades the potential because the building creates turbulence. Obviously, wind speeds also heavily depend on the tower height, since they significantly rise as the distance above the ground increases. Siting the wind turbine correctly (out in the open and preferably on higher grounds) is therefore another essential step for realizing the full potential of the wind system: out in the open and free of obstacles (Bartmann, *et al*., 2009).

The table presented below summarizes the typical energy options and costs in rural Kenya. On monthly average and whatever the solutions, rural households have to spend considerable amount for their energy needs compared to their income. Up to 25% of the income can be spent into energy expenditure.

Table 4.2: Main power providers in isolated areas of Kenya

	Rural Electrification Programme Isolated grid		Independent mini-grid		Home solutions	
			Diesel-based	Hydro-based	12VDC solar-home system and battery-based systems	Dry Cell and kerosene
Power delivery capacity	0-100s kWh/month				<6 kWh/month	>0.5 kWh/month
Appliances	Capacity to power most appliances (provided rural people can afford them)				Lights, TV, radio, cell phone, small motors	Kerosene lamp radio
kWh cost	Production US$ 0.3/kWh	Cons. tariff US$ 0.11/kWh	> US$0.3/kWh	US$ 0.16-0.21 /kWh	+- US$ 0.5/kWh	US$ 40/kWh
Real monthly costs paid by consumers	US$ 5-20		US$ 10-50	US$ 5-50	US$ 2 (low maintenance) US$ 5-15 in fee-for-service	US$ 5-15

The Sessional Paper 2004 reports that "it costs more than KSh.1.2million (USD 15000) on average to construct a kilometre of an 11kV or a 33kV line. Thus, the average cost of supplying a rural consumer was KSh.180000 (USD 2250), which is about seven times the national per capita income in 2002." Electricity tariff countrywide is at KSh 8/KWh (USD 0.1/KWh). (GOK, 2004).

Below table gives an overview of the characteristics of the different SWT types on the Kenyan market

Table 4.3: Characteristics of the different SWT types on the Kenyan market

Aspect	Informal manufacturing	Local manufacturing	Imported turbines
Production	(Very) small scale Local scrap/ spare parts	Small scale local (quality) materials	Mass scale
Power	20-300W	200W – 10kW	200W-10kW
Efficiency	Very low	Medium	High
Cost	Very low – low	Medium	High
Quality	Low	Medium	Reliable and well-tested
Repair and maintenance	Can be locally repaired (spare parts available)	Can be locally repaired Spare parts available	Local skills and spare parts may not be available

The cost is a critical design criterion, but so is the performance and turbine quality. For this reason, turbines are available in the local market at a variety of sizes of medium cost and reasonable efficiency. For the smaller sizes (150W-300W), prices range between Ksh 100.000 and Ksh 200.000 (Turbine, tower and electronics). Turbines of ca. 1KW rated power are available for a total cost of KES 280.000–350.000. For power outputs of around 3KW, which is the maximum size that can mostly be found installed, turbine prices rise up to KES 800.000 (Craftskills Ltd, 2010).

The cost of production of this studies Rotor blade with all components was about Kshs. 120,000.as shown in the table below This cost included buying of the shaft, hubs and bearing and the blades (refer to Appendix B for blade cost production quote).

Table 4.4: Cost description for developing the darrieus turbine

Cost description for developing the darrieus turbine		**Amount (Ksh)**
Materials and fabrication costs of Glass Reinforced plastic.	model Moulding Laminating drying trimming	70,000
Blades testing and assessment	- Laboratory	10,000
Tools & Materials	- Scissors/Pliers - Screw driver - Silicon gun - Petroleum grease - Thick gloves & disposable gloves - Syringe - Mouth cap	10,000
Mechanical, Electrical and Performance Tests		30,000
TOTAL		**120,000**

4.3 Cost-benefit analysis

When designing small-scale renewable energy systems efficiency is not the ultimate parameter that we should look into. One reason is that we can afford building a larger energy converter if that would allow the optimisation of other parameters. Another reason is that cost and simplicity of design are much more important than efficiency and productivity. The turbine design is much simpler than any other turbine and avoids the use of complex aerofoil shapes and structures. The cost of this turbine is at minimum when compared with conventional HAWT structures.

Practical applications of small VAWTs are primarily the following:

1. Water pumping

Due to low rotational speed and high torque it is suitable to couple the hereby proposed wind rotor with a reciprocating pump that is mainly used for agricultural or household water pumping.

2. Domestic electricity generation

Expected turbine rotational speed is around 50 RPM at 4 ms-1 wind speed, therefore a high gear ratio is required to generate electricity for domestic usage or to connect to the grid. Alternatively, multipole electrical generators can be used for direct coupling with the wind rotor.

The cost of generated electricity can be estimated as the system cost divided by the total energy yield in the turbine's lifetime. In this analysis, it was assumed that the turbines have a life-time of at least 20 years and that during this life time they will operate with the same efficiency as during the test period. Additional cost for repair and maintenance have been neglected. The cost of generated electricity in ksh per kWh can then be calculated as (Dayo, 2013)

$$\boldsymbol{C = \frac{Ce}{T \times E_{ay(meas)}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{17}$$

where Ce is the actual system cost, T is the turbine's lifetime and E ay(meas) is the measured annual energy yield. However, it must be pointed out that the life time of a small wind turbine depends partly on the design and manufacturing process. Furthermore, cost of repair and maintenance could become a major cost determining factor over the turbine's lifetime.

In performing a cost efficiency analysis of the turbines, it is desirable to have systems with

low KSH/KWh. Our turbines using the above calculation considering an annual energy yield 245 Kwh and the system cost of Ksh 120,000 provided in table 4.4 will have electricity generation costs was USD 0.2 per KWh. This cost compares with the rural electrification cost shown in table 4.2.

Another parameter that was considered to check viability was the capacity factor.

Capacity factor is defined as:

$$CF = \frac{Energy\ produced\ by\ the\ system\ during\ one\ year}{Total\ energy\ which\ can\ be\ produced}$$

Capacity factor of the turbine = 24.3

According to the wind economics researches (Forsyth *et al.,* 1999), viable capacity factor for a wind power system lies between 27 and 30. Therefore, the CF value is close to being viable and it can be concluded that this type of turbines is most appropriate for areas with strong winds which are available throughout the year.

A comparison was also done to compare prices with local manufactures. Result of a research that was conducted by Rencon Associates Ltd, on behalf of JICA, Kenya Office (Ltd 2013) on the main manufacturers/distributors of wind turbines and mills in Kenya are shown in table 4.5.

Using the questionnaire found in appendix B Technology mapping was conducted through consulting various industries. Players/promoters gave the various HAWT models that are sold/manufactured in Kenya (table 4.5). Even though most of the local suppliers do not supply VAWT, their international price of VAWT of same sizing as developed in this study was found to be about US$ 2,000. This makes it more expensive when compared to the blade developed in this study.

Table 4.5: List of current wind turbine models in the Kenyan Market

	Dealer / Manufacturer	**HAWT Model**	**Blade Diameter (m)**	**Nominal Power (W)**	**PRICE (Kshs)**
1.	RIWIK	Airflow 350	1.8	350	135,000
		Airflow 800	3.0	800	189,000
		Airflow 1000	4.2	1,000	262,000
2.	WindGen EA	Twiga Turbine	1.6	200	56,000
		Simba Spinner	2.1	400	99,000
		Rhino Rotor	3.1	1,000	149,000
3.	Craftskills EA	Craftskills EA Turbine		150	33,500
		Craftskills EA Turbine		300	53,500
		Craftskills EA Turbine		700	103,500
		Craftskills EA Turbine		1,200	138,700
		Craftskills EA Turbine		1,800	170,100
		Craftskills EA Turbine		2,500	215,500
		Craftskills EA Turbine		3,000	238,000
		Craftskills EA Turbine		6,000	292,000
		Craftskills EA Turbine		9,000	565,000
		Craftskills EA Turbine		12,000	960,000
4.	Kenital solar	Wind Turbine		400	165,000

		Wind Turbine		900	354,000
		Wind Turbine		1,000	375,000
		Wind Turbine		1,300	435,000
5.	Davis & Shirtliff	TY 400	1.8	400	95,000
		TY 600	1.8	600	105,000
		TY 1000	2.8	1,000	190,000
6.	Chloride Exide	Air Breeze-Marine		200	120,000
		Air Breeze-Land		200	98,000
		Air X-Marine		400	114,000
		Air X-Land		400	98,000
		Whisper-Land		100-900	334,000
		Whisper-Marine		100-900	334,000
		Whisper-Land		200-1000	366,000
7.	Powerpoint Systems EA	Taifu		400	76,000
		Taifu		600	86000
		Taifu		1000	124000
		Air Breeze-Marine		200	120,000
		Air Breeze-Land		200	98,000
		Air X-Marine		400	114,000
		Air X-Land		400	98,000
		Whisper-Land		100-900	334,000
		Whisper-Marine		100-900	334,000
		Whisper-Land		200-1000	366,000

4.4 Social and Environmental Impact

The development of small wind energy impacts the Kenyan society on a wide range of socioeconomic and environmental aspects.

The Kenyan SWT activities have shown that small wind systems have a large social impact. Schools have for instance proven to benefit from SWT electricity by the development of morning/evening classes and access to computer as a modern education method.

Actors have also learnt that electricity enables ICT and TV services, which in turn provides access to information to the most remote communities. Living conditions have been proven to increase by better lighting and kerosene cost reduction. Besides that, in some cases, SWTs have shown to save time since they allow for battery charging at home instead of at a (long) walking distance (RISO DTU, 2009; Berges, 2007).

Moreover, pilot projects of non-profits and universities have also shown that electricity from SWTs enables the use of electric tools and equipment and thereby enhances productivity and revenues of many small businesses such as welders, carpenters and tailors. If the grid is not available and the wind resource is good, some experiments have learnt that the energy produced by SWTs is cheaper than other off-grid alternatives such as PV and diesel generators, especially if the fuel supply is far-off. Actors have also learnt about the health benefits of introducing green electricity; the utilization of traditional energy sources such as kerosene for lightning have shown to be significantly decreased with the introduction of an SWT (Berges, 2007; UNIDO, 2011).

Furthermore, small wind systems positively impact the environment. With its zero emissions, small wind turbines have also proven to contribute to the reduction of carbon emissions through biomass and fossil fuels (UNIDO;n,d). Moreover, small wind turbines produce some noise contrary to the silent grid (Dunnett, *et al*., 2001). However, when compared to the most frequent off-grid alternative diesel generators they are far quieter. visual impacts of small wind turbines (Dunnett, *et al.*, 2001). With its 10m height, small wind turbines are considered landmark in their surroundings.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From the results and analysis, it is concluded that some adjustments can be done in the optimal design to improve starting performance. Another conclusion is that to get high power production and starting performances, increasing chord length distribution, Radius or blade number are key during design process and generator choice is also key step in the SWT design process.

According to the observations and data analysis it can be concluded that the Cp value of the 1 x 1 m (aspect ratio of 1) turbine rotor is 0.10 and the related optimum tip speed ratio is 0.35. Although it was possible to achieve satisfactory results with the available resources, far more accurate experiments could be done by proper wind tunnel testing. Therefore, a

wind tunnel test is recommended for the proposed turbine model. The prototype performance at speed of 14 m/s gave the highest power of 190 W at 280 RPM, 12 m/s gave the highest power as 156 W at 230 RPM, 10 m/s gave the highest power as 120W at 180 rpm while 8 m/s gave the highest power as 96 W at 140 RPM. 2850 is the rated RPM for the Generator. The turbine torque was 1.56Nm at an RPM of 175. The turbine has high torque but low rotational speed.

It is concluded that a high gear ratio generator may achieve higher power output. Alternatively, multipole electrical generators can be used for direct coupling with the wind rotor.

The cost of production of this studies Rotor blade with all components was about Kshs. 50,000. This cost included buying of the shaft, hubs and bearing (Kshs. 25,000) and the blades amounted to about Kshs. 21,000. When compared to a HAWT turbine of same sizing it costs between 100000-200000. Most of the local suppliers do not supply VAWT, the international price of VAWT of same sizing as developed in this study is about US$ 1,000. In conclusion the blade produced in this study is cheaper when compared to locally produced HAWT and VAWT prices in international market.

Three bladed rotors would be the most adapted configurations for the target low/moderate wind climate given the constraint of direct driven connection to permanent magnet generator. NACA 0021 air foils provide very interesting characteristics for high power production and starting performances in low/moderate wind climates Favourable load variations on the turbine may be achieved with more than three blades but a higher manufacturing cost

5.2 Recommendations

Various challenges were encountered in the course of this research. For further research the following recommendations are necessary;

Obtain a generator for low wind speeds or a multi-speed geared generator capable of stepping up the low rotational speeds of the turbine to high speeds compatible with such a generator.

For actualization of the project, the next step should be setting up of training workshops for manufacturers of such turbines. Further training would require to be given to the operators of the wind turbines on their maintenance.

To Design a robust system that need little maintenance, promoting local skills and equipment should be the chore ideas of any project for designing of small wind turbines adapted to operation in offgrid places

This study is based on a single project and therefore it would be interesting to face the present conclusion with the evaluation of other wind-based rural electrification projects;

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APPENDICES

Appendix i: Questionnaire

Interviewer:…………………….... Date: …………….. Serial Number: ……………………………

JOMO KENYATTA UNIVERSITY OF AGRICULTURE AND TECHNOLOGY
Setting trends in Higher Education, Research and Innovation

DEVELOPMENT OF A LOW COST, LOCALLY MANUFACTURED, EFFICIENT WIND PUMP/TURBINE FOR USE IN WATER PUMPING IN KENYA

About the project

JKUAT and the NCST are undertaking a project that seeks to engage the stakeholders in the wind energy sector in the development of a low cost, efficient, locally manufactured small wind turbine to be used for water pumping. In lieu of your participation in the stakeholder meeting in November last year, your firm is one of those preselected to work with us in the development of this wind turbine.

As a precursor to begin the development process, this questionnaire seeks to understand how role in the wind turbine sector, the challenges experienced in manufacture, sale and maintenance of wind turbines and obtain your opinion on the challenges, expectations and possible solutions to better provide a niche for the small wind turbine. Your support and participation is thus highly appreciated.

The development team

Section 1: Developer information

Name of Organization: ……………………………………………………………………………………….

Contact person(s): ……………………………………………… Physical Address: ………………………………………………

Postal address: ………………………… Postal Code: …………………………. Town/City: …………………………….

Tel: ………………………………………… Email: …………………………………………. County: …………………………….

Organization Type: NGO/ CBO ☐ Registered Company ☐ Educational institution ☐ Others ☐ (if others please specify ……………………………………)

Number of year involved in wind issues: 0 – up to 2 years ☐ 3 – up to 5 years ☐ over 5 years ☐

Nature of wind business (tick all applicable): Manufacturing ☐ Import &/or export ☐ Reseller ☐ Distributor ☐ assembler ☐ Others ☐ (if others please specify **……………………………………………)**

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Section 2: Technology information

Model Number	Rated Capacity (Watts) or relevant units	Rotor Diameter & tower Height	Cost of installation (KES)	Cost of Tower (KES)	Cost (KES) of Wind turbine *	HAWT or VAWT	Generator only	Generator plus tower
							☐	☐
							☐	☐
							☐	☐
							☐	☐

***Indicate if the wind turbine cost is only for generator or is for generator plus tower**

Where in Kenya is the technology installed and how many

Model Number	Where installed (county and nearest town)	Number installed	Year of installation	Installation cost	Cost (KES) of Wind turbine *	Currently working	Not working or status unknown
						☐	☐
						☐	☐
						☐	☐
						☐	☐

Description of Rotor blade used (Photograph included - yes ☐, photo number ………..)

………

………

Description of Transmission system used (Photograph included - yes ☐, photo number ………..)

………

………

Performance rating of the wind turbines

Model Number	Rotor system	Transmission system	Tower	Power production	End user view of performance	Require further development
						☐
						☐
						☐
						☐

(*Use a rating of 1= Excellent/Good, 2 = Average and 3 = poor)**

Section 3: Field experience of the technology

Technology SWOT analysis

Component	Advantages / opportunities	Challenges & disadvantages	Mainly affects which model
Rotor system			
Transmission system			
Tower			
Power production			

Policy, legal and regulatory framework

Component	Advantages / opportunities	Challenges & disadvantages	Mainly affects which model
Policy			
Legal & regulatory			
Financing			
Sale & distribution			
Operation & maintenance			
Others (please specify)			

Interviewer:……………………..... Date: …………….. Serial Number: ……………………………

Wind turbine manufacturing / Assembling process

Component	Assembling or manufacturing	Description of the process Photographs included - yes ☐, photo number .... Equipments list used included - yes ☐, List of materials used to make component included - yes ☐
Rotor system		…………………………………………………………………… …………………………………………………………………… …………………………………………………………………… …………………………………………………………………… ……………………………………………………………………
Transmission system		…………………………………………………………………… …………………………………………………………………… …………………………………………………………………… …………………………………………………………………… ……………………………………………………………………
Tower		…………………………………………………………………… …………………………………………………………………… …………………………………………………………………… …………………………………………………………………… ……………………………………………………………………
Complete system		…………………………………………………………………… …………………………………………………………………… …………………………………………………………………… …………………………………………………………………… ……………………………………………………………………

Wind turbine manufacturing / Assembling Materials and Equipment

Component	Assembling or manufacturing	Equipment required	Materials used to make the components
Rotor system		……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ………………………………………	……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ………………………………………
Transmission system		……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ………………………………………	……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ………………………………………
Tower		……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ………………………………………	……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ………………………………………
Complete system		……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ………………………………………	……………………………………… ……………………………………… ……………………………………… ……………………………………… ……………………………………… ………………………………………

Appendix ii: Quotation from Local Wind Manufacturers

RIWIK

QUOTATION

To: Joel Perrodo   Date: 10/05/2013

1. COMPONENTS OF THE SYSTEM AS OFFERED

Based on an estimation of your future energy needs (see below), we composed an off-grid energy solution with the following components:

DESCRIPTION	QTY	RATE	TOTAL	16% VAT
Wind turbine, Airflow 800. 800W, 48V	1	194,000	194,000	
Wind turbine charge controller, Morningstar. TS 45	1	18,896	18,896	
Batteries, Trojan L16RE-B. 370Ah, 6V	24	30,994	743,850	-
Solar panels, Canadian Solar. 240W, 24V	24	32,729	785,506	-
Inverter, Victron, Pure Sine wave. QUATTRO 10000VA, 48V	1	529,031	529,031	-
Solar charge controller, Morningstar, TS-MPPT-60	2	61,133	122,265	-
Solar Lightning arrestor 302/303	3	8,500	25,500	-
Solar breakers, 15A	9	2,600	23,400	-
MNPV12	1	25,565	25,565	-
Victron mega fuse 125A with holder	1	4,446	4,446	-
MN DC Breaker 175Amp	1	12,782	12,782	-
DC wiring 6mm2	120	153	18,360	2,938
DC wiring 16mm2	8	360	2,880	461
Grounding wiring	25	900	22,500	3,600
Battery cable 70mm2	25	690	17,250	2,760
Grounding kit	1	2,000	2,000	320
MC4 connections	11	3,100	34,100	5,456
Accessories	3	4,000	12,000	1,920
Solar frame	24	3,500	84,000	13,440
Change over switch	1	16,000	16,000	2,560
AVS60	1	9,000	9,000	1,440
Installation	24	4,000	96,000	15,360
			SUBTOTAL Zero rated	**2,485,240**
			Subtotal vatable	**314,090**
			VAT (16%)	**50,254**
			GRAND TOTAL (Kshs)	**2,849,585**

PO Box 68115-00200, Nairobi **T:**+254708725026 **E:** info@riwikeastafrica.com **W:** www.riwikeastafrica.com

2. NOTES/ASSUMPTIONS

- The system price is exclusive wiring in the house.
- No consumer unit and AC MCB switches are quoted. If needed, it will be added on the quotation.
- The system design is based on the assumption that the solar panels will be mounted on an existing structure.

3. VAT

16% VAT has been charged where applicable. The wind turbine, solar panels and electronics are exempted from VAT.

4. VALIDITY

The prices in this document are valid for 15 days from the above date.

5. ENERGY PROFILE

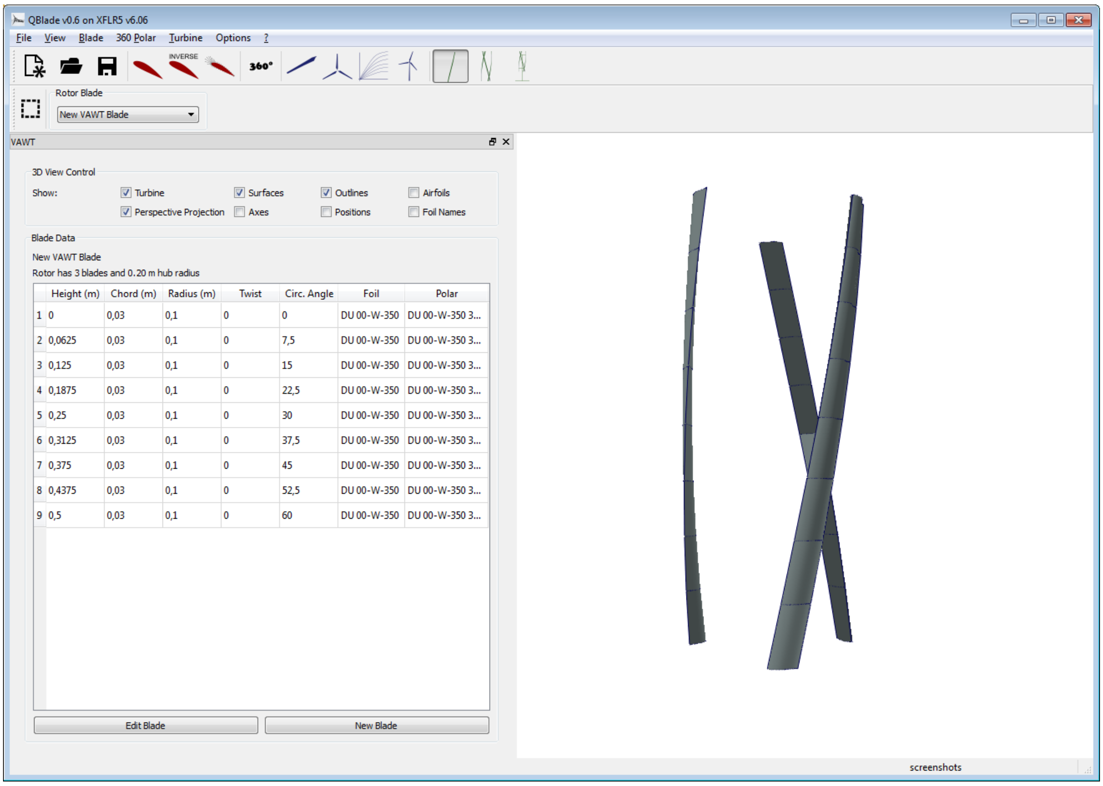
The energy system was designed based on the following energy profile:

Devices	Number of devices	Power usage (Watts)	Hours per day	Days per week	Weekly energy usage (Watt hours)	Power load (Watts)
Light bulbs	140	11	4.0	7.0	43120	1540
Light bulbs	30	11	10.0	7.0	23100	330
Iron	1	1400	0.5	7.0	4900	1400
Toaster	1	850	0.2	7.0	1190	850
Blender	1	500	0.2	7.0	700	500
Ice scream maker	1	250	0.2	7.0	350	250
Cream separator	1	70	0.2	7.0	98	70
Radio, mobile phone on circuit	4	50	4.0	7.0	5600	200
Music installation	1	500	6.0	7.0	21000	500
Computers	2	200	4.0	7.0	11200	400
Television and DVD	2	250	5.0	7.0	17500	500
DC Refrigerator 225L	2	na	na	7.0	1960	Na
DC Freezer 165L	2	na	na	7.0	6230	Na
Required inverter size (Watt)						6540
Weekly energy consumption devices (Watthours)					136948	

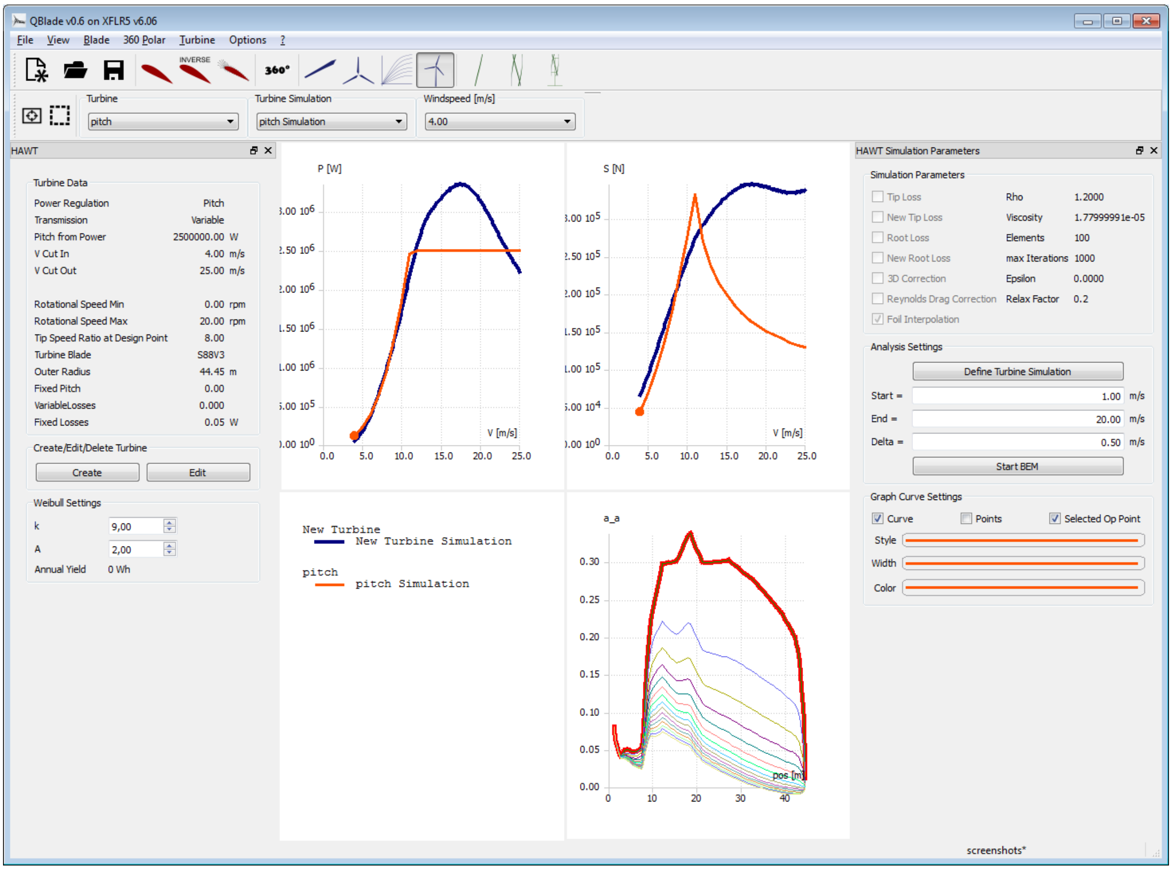
Appendix iii: NACA 0021 Look Up Table

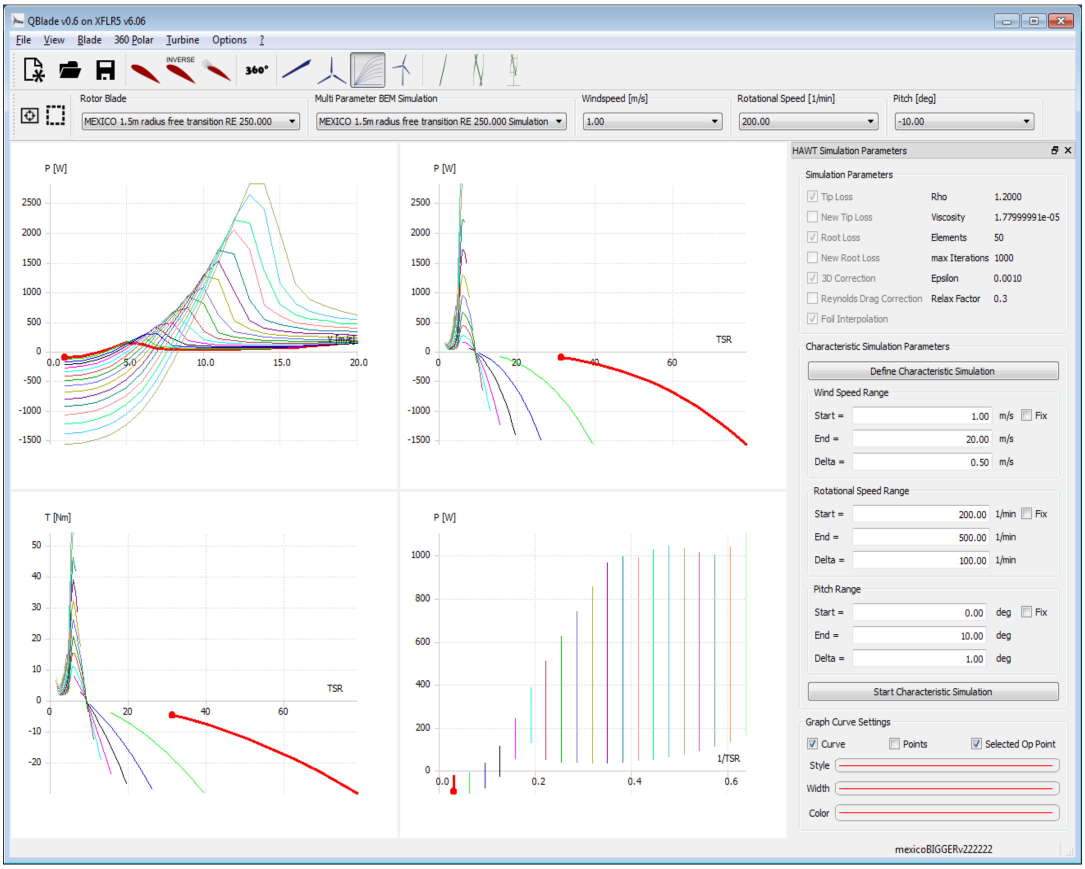
Ordinates		chord	28 cm
x(%c)	y(%c)	x	y
0	0,000	0	0
1,25	3,315	0,35	0,9282
2,5	4,576	0,7	1,2813
5	6,221	1,4	1,7419
7,5	7,350	2,1	2,058
10	8,195	2,8	2,2946
15	9,354	4,2	2,6191
20	10,040	5,6	2,8112
25	10,397	7	2,9112
30	10,504	8,4	2,9411
40	10,156	11,2	2,8437
50	9,265	14	2,5942
60	7,986	16,8	2,2361
70	6,412	19,6	1,7954
80	4,591	22,4	1,2855
90	2,534	25,2	0,7095
95	1,412	26,6	0,3954
100	0,221	28	0,0619
L.E. radius (%c)		4,85	

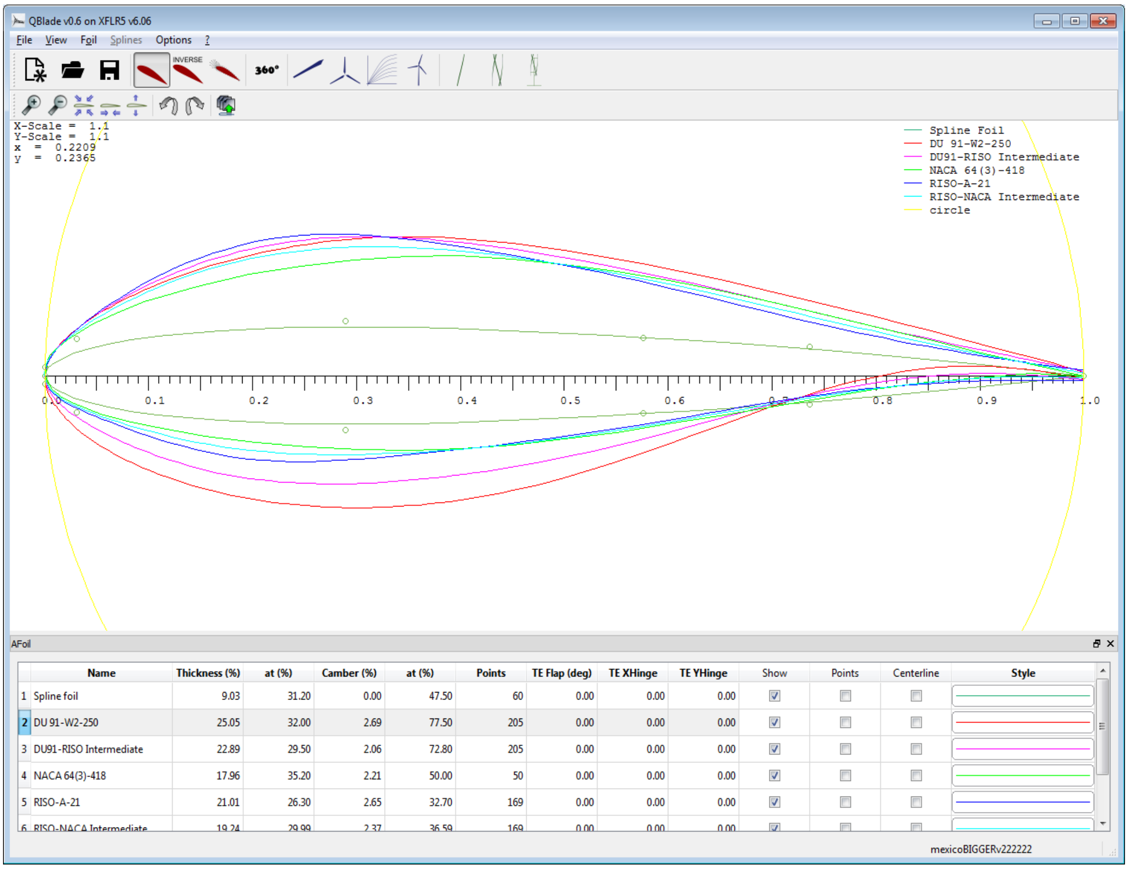
Appendix iv: Qblade Software screen shots



	Height (m)	Chord (m)	Radius (m)	Twist	Circ. Angle	Foil	Polar
1	0	0,03	0,1	0	0	DU 00-W-350	DU 00-W-350 3...
2	0,0625	0,03	0,1	0	7,5	DU 00-W-350	DU 00-W-350 3...
3	0,125	0,03	0,1	0	15	DU 00-W-350	DU 00-W-350 3...
4	0,1875	0,03	0,1	0	22,5	DU 00-W-350	DU 00-W-350 3...
5	0,25	0,03	0,1	0	30	DU 00-W-350	DU 00-W-350 3...
6	0,3125	0,03	0,1	0	37,5	DU 00-W-350	DU 00-W-350 3...
7	0,375	0,03	0,1	0	45	DU 00-W-350	DU 00-W-350 3...
8	0,4375	0,03	0,1	0	52,5	DU 00-W-350	DU 00-W-350 3...
9	0,5	0,03	0,1	0	60	DU 00-W-350	DU 00-W-350 3...


QBlade v0.6 on XFLR5 v6.06
File View Blade 360 Polar Turbine Options ?
Turbine
pitch
Turbine Simulation
pitch Simulation
Windspeed [m/s]
4.00
HAWT
Turbine Data
Power Regulation Pitch
Transmission Variable
Pitch from Power 2500000.00 W
V Cut In 4.00 m/s
V Cut Out 25.00 m/s
Rotational Speed Min 0.00 rpm
Rotational Speed Max 20.00 rpm
Tip Speed Ratio at Design Point 8.00
Turbine Blade S88V3
Outer Radius 44.45 m
Fixed Pitch 0.00
VariableLosses 0.000
Fixed Losses 0.05 W
Create/Edit/Delete Turbine
Create
Edit
Weibull Settings
k 9,00
A 2,00
Annual Yield 0 Wh
P [W]
V [m/s]
S [N]
New Turbine
New Turbine Simulation
pitch
pitch Simulation
a_a
pos [m]
HAWT Simulation Parameters
Simulation Parameters
Tip Loss
New Tip Loss
Root Loss
New Root Loss
3D Correction
Reynolds Drag Correction
Foil Interpolation
Rho 1.2000
Viscosity 1.77999991e-05
Elements 100
max Iterations 1000
Epsilon 0.0000
Relax Factor 0.2
Analysis Settings
Define Turbine Simulation
Start = 1.00 m/s
End = 20.00 m/s
Delta = 0.50 m/s
Start BEM
Graph Curve Settings
Curve
Points
Selected Op Point
Style
Width
Color
screenshots*


QBlade v0.6 on XFLR5 v6.06
File View Blade 360 Polar Turbine Options ?
Rotor Blade
MEXICO 1.5m radius free transition RE 250.000
Multi Parameter BEM Simulation
MEXICO 1.5m radius free transition RE 250.000 Simulation
Windspeed [m/s]
Rotational Speed [1/min]
Pitch [deg]
HAWT Simulation Parameters
Simulation Parameters
Tip Loss
New Tip Loss
Root Loss
New Root Loss
3D Correction
Reynolds Drag Correction
Foil Interpolation
Rho 1.2000
Viscosity 1.7799999e-05
Elements 50
max Iterations 1000
Epsilon 0.0010
Relax Factor 0.3
Characteristic Simulation Parameters
Define Characteristic Simulation
Wind Speed Range
Rotational Speed Range
Pitch Range
Start Characteristic Simulation
Graph Curve Settings
Curve
Points
Selected Op Point
Style
Width
Color
mexicoBIGGERv222222


QBlade v0.6 on XFLR5 v6.06
File View Foil Splines Options ?
X-Scale = 1.1
Y-Scale = 1.1
x = 0.2209
y = 0.2365
Spline Foil
DU 91-W2-250
DU91-RISO Intermediate
NACA 64(3)-418
RISO-A-21
RISO-NACA Intermediate
circle
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
AFoil
Name | Thickness (%) | at (%) | Camber (%) | at (%) | Points | TE Flap (deg) | TE XHinge | TE YHinge | Show | Points | Centerline | Style
1 Spline foil 9.03 31.20 0.00 47.50 60 0.00 0.00 0.00
2 DU 91-W2-250 25.05 32.00 2.69 77.50 205 0.00 0.00 0.00
3 DU91-RISO Intermediate 22.89 29.50 2.06 72.80 205 0.00 0.00 0.00
4 NACA 64(3)-418 17.96 35.20 2.21 50.00 50 0.00 0.00 0.00
5 RISO-A-21 21.01 26.30 2.65 32.70 169 0.00 0.00 0.00
6 RISO-NACA Intermediate 19.74 29.99 2.37 36.59 169 0.00 0.00 0.00
mexicoBIGGERv222222

Appendix v: Publications

Open Access Journal

Journal of Sustainable Research in Engineering Vol. 2 (3) 2015, 92-99

Journal homepage: www.jkuat-sri.com/ojs/index.php/sri/index

Development of a Low Cost Rotor Blade for a H - Darrieus Wind Turbine

Haroub Ahmed Haroub[1*], Francis Xavier Ochieng[1] and Joseph N. Kamau[2]

[1]*The institute of Energy and Environmental Technology (IEET) – JKUAT, P. O. Box 62000-00200, Nairobi, Kenya.*

[2] *Department of Physics, JKUAT, P. O. Box 62000-00200, Nairobi, Kenya.*

**Corresponding author- E-mail: bharoub@gmail.com*

Abstract A three bladed vertical axis wind turbine with a target performance of 500W was designed and fabricated. The material used was Glass fiber reinforced plastics (GFRP). The study focused on Blade design where a numerical optimization process of the design was done to come up with parameters for the rotor blades. The chosen sizing was a rotor diameter of 2m and length of 1.6 m with a chord length of 0.2 m. A NACA 0021 air foil was chosen because of its thickness (21% of chord) and its self-starting behavior. Blade production process involved making of the master blade to form the mould. The mould was used to make the blade copies that was later laminated, dried, trimmed, and smoothed. The power coefficient was tested using a wind fan with wind speeds ranging from 4 m/s to 15 m/s. A direct drive Axial Flux Permanent Magnet (AFPM) generator with a rated RPM of 280 developed for small scale vertical axis wind turbine (VAWT) was coupled to the turbine rotors to determine the electricity generation capacity. A battery was used to provide the load in the experiment and the synchronized frequency controlled by an inverter. A speed of 14 m/s gave the highest power of 190 W at 280 rpm, 12 m/s gave the highest power as 156 W at 230 rpm, 10 m/s gave the highest power as 120W at 180 rpm while 8 m/s gave the highest power as 96 W at 140 rpm. The turbine torque was 1.56Nm at an RPM of 175. It was noted the turbine has high torque but low rotational speed and with a high gear ratio generator may achieve higher power output. The cost of production of the Rotor blade with all its components was approximately Kshs. 50,000. This cost included buying of the shaft, hubs and bearing totaling to Kshs. 25,000 and the blade production cost Kshs. 21,000. When compared to a HAWT turbine of same sizing cost in the local market the price ranges from KSH 100000 to KSH 200000. Most of the local suppliers do not supply VAWT; the international price of VAWT of same sizing is about US$ 1,000. In conclusion the blade produced in this study is cheaper when compared to locally produced HAWT and VAWT prices in international market.

Keywords Vertical axis turbine, rotor blade, H-Darrieus, Kenya.

1. Introduction

There is significant potential to use wind energy for grid connected wind farms, isolated grids (through wind-diesel hybrid systems) and off-grid community electricity and water pumping in Kenya. An average of 80-100 small wind turbines (400W) have been installed to date, often as part of a Photovoltaic (PV)-Wind hybrid system with battery storage[1]. Most of these wind turbines are imported although a few Kenyan companies have recently started locally manufacturing wind turbines ranging from 150W – 6kW and have installed 50 turbines to date. Wind pumps are more common than wind turbines, 2 local companies manufacture and install wind pumps. Installations are in the range of 300-350 [2].

According to Global Tracking Framework report [3] under the Sustainable Energy for All Initiative to measure levels of energy, development of market for locally manufactured small energy technologies was noted to be one of the indicators to attain energy security and exploitation of renewable energy sources. The Government of Kenya Wind Resource Assessment report [4] shows average wind speeds of 4 - 5 m/s that could provide excellent opportunity for enhancing access to modern energy sources in rural areas using renewable energy sources. However, the cost of acquisition is proving to be inhibiting as demonstrated by the slow uptake of the technology given the massive potential the country holds [5][6]. The current price for a 0.4 KW wind turbine made of cast aluminium and carbon fibre is between KShs 76,000 and KShs 110,000 and 1KW costs KShs 450,000.

The Kenya national energy policy objective is to ensure adequate secure, affordable, sustainable and reliable supply of energy to meet national and county development needs, while protecting and conserving the environment. The policy also aims to prioritize and promote the development of local technologies in energy development and delivery. However this aspect is yet to be fully realized and some of the hindering factors include low adoption of renewable energy technologies despite the huge potential the country have. The low adoption is accelerated by the high cost of imported turbines. Currently, there exist small scale Pico-wind turbine manufactures, though efficiency is noted to be pretty low, these systems have not really penetrated the market. The existence of these manufacturers is rarely known by potential users in addition the pricing of these turbines is no clear and consistent [7].

To facilitate uptake of these technologies, development of efficient low-cost wind turbines stands to be a major determinant coupled with a strong strategy to promote commercialization on these technologies.

The straight bladed Darrieus vertical axis wind turbine (VAWT) is very attractive for its low cost and simple design [8]. Anyone with common workshop materials could build and would make a difference in the living conditions of people with low income. This justifies the need to undertake this research.

2. Theoretical Optimization

The power of the wind is proportional to air density, area of the segment of wind being considered, and the natural wind speed. The relationships between the above variables are provided in equation (2.1) below [9].

$$P_w = \frac{1}{2}\rho A u^3 \quad (1)$$

Where;

Pw: power of the wind (W)

ρ : air density (kg/m3)

A: area of a segment of the wind being considered (m²)

u: undisturbed wind speed (m/s)

At standard temperature and pressure (STP = 273K and 101.3 kPa), equation 1 reduces to equation 2

$$P_w = 0.647 A u^3 \quad (2)$$

A turbine cannot extract 100% of the winds energy because some of the winds energy is used in pressure changes occurring across the turbine blades. This pressure change causes a decrease in velocity and therefore usable energy. The mechanical power that can be obtained from the wind with an ideal turbine is given in equation 3 [10]:

$$P_m = \frac{1}{2} M \left(\frac{16}{27}\right) A u^3 \quad (3)$$

Where;

Pm: mechanical power (W)

In equation 3, the area, A, is referred to as the swept area of a turbine. For a VAWT, this area depends on both the turbine diameter and turbine blade length. For an H-type VAWT the equation for swept area is:

$$A_s = D_t l_b \quad (4)$$

Where:

A_s: swept area *(m²)*

D_t: diameter of the turbine *(m)*

l_b: length of the turbine Blades *(m)*

The constant 16/27 = 0.593 from equation (3) is referred to as the Betz coefficient. The Betz coefficient tells us that 59.3% of the power in the wind can be extracted in the case of an ideal turbine [11]. However, an ideal turbine is a theoretical case. Turbine efficiencies in the range of 35-40% are very good, and this is the case for most large-scale turbines. It should also be noted that the pressure drop across the turbine blades is very small, around 0.02% of the ambient air pressure. Equation (3) can be re-written as;

$$P_m = C_p P_w \quad (5)$$

Where *Cp:* coefficient of performance.

The coefficient of performance depends on wind speed, rotational speed of the turbine and blade parameters such as pitch angle and angle of attack. The pitch angle for a HAWT is the angle between the blades motion and the chord line of the blade, whereas for a VAWT the pitch angle is between the line perpendicular to the blades motion and the chord line of the blade [12]. The angle of attack is the angle between the relative wind velocity and the centerline of the blade. For fixed pitch turbines, these angles do not change and the Cp is directly related to the TSR. A typical Cp value for the turbine design was adopted from the table below. These values were derived from [13].

Table 1: Typical Cp values for various wind turbines

Wind System	Efficiency %	
	Simple Construction	Optimum Design
Multi bladed water pump	10	30
Sail wing water pump	10	25
Darrieus water pump	15	30
Savonius Wind pump	10	20
Small prop-type wind charger (up to 2KW)	20	30
Medium prop-type wind charger (2 to 10KW)	20	30
Small prop-type wind charger (over 10KW)		30 to 45
Darrieus wind Generator	15	20

A model developed using Qblade an open source turbine calculation software seamlessly integrated into XFOIL, an airfoil design and analysis tool. The model helps avoid conducting repetitions and lengthy calculations by hand. The key inputs include TSR, and solidity, as solidity has effects on the chord length and blade height of the airfoil. In order to speed up the optimization process, some of the parameters were fixed. The fixed parameter was the design airspeed and the blade swept area. The wind speed was kept constant throughout the analysis at the average wind speed value for of 6m/s. The blade length and rotor radius have a major contribution in the torque behavior of the turbine as can be deduced from the torque equation. In general as bigger these parameters, bigger the torque produced. These parameters are involved also in the solidity calculation. The solidity becomes an important parameter when scaling down or up wind turbines and also determines the applicability of the momentum model. The radius and blade variation analysis was done maintaining constant swept area.

With a desired power output of 500w simplified equations from the blade element momentum were used to calculate the dimensions of the blade the design values used are as shown in the table 2 below;

Table 2: Sizing for the model inputs

Undisturbed Wind Speed	6 m/s
Density of air	1.204 kg/m³
Viscosity of air	1.81×10^{-05}Ns/M²
Rated wind speed	9 m/s
TSR	4
Solidity	0.15
Rotor Diameter	2 m
number of airfoils/blades	3
Blade height	1.60 m
Expected rated power	500 W
NACA air foil	0021
Estimated coefficient of performance	0.1

3. Materials and Methods

The study conducted Field and market assessment of the locally produced small wind turbines in Kenya through Field surveys, interviews and questionnaires. The methodology involved two stages namely; i) Design and fabrication ii) turbine testing.

The aerofoil section was designed in accordance with the NACA 0021 profile shown in figure 1 and drawn using the AutoCAD program. This NACA 0021 profile was chosen for its good lift characteristics and flat-wise strength [14].

Fiberglass composites or fiber reinforced plastics was the chosen material for VAWT rotor blades[15]. These composites have low density, good mechanical properties, excellent corrosion resistance and versatility of fabrication methods [16]. Fiberglass composites already see widespread in HAWT blades where their strong performance makes them the material of choice [17]. Fiberglass composites were therefore the strong candidate for small, experimental VAWT research.

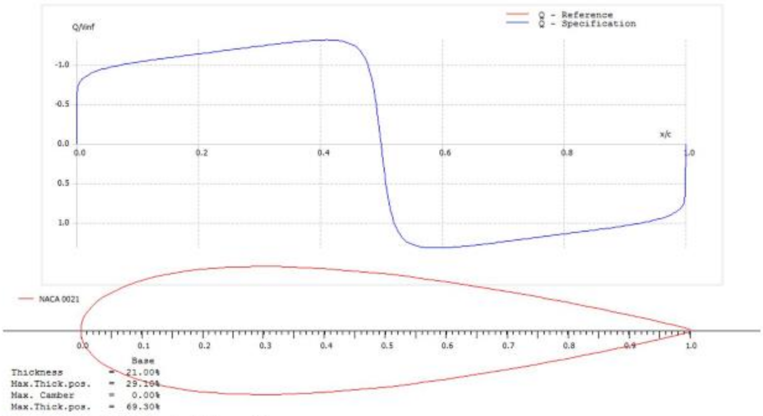


Fig. 1. NACA 0021 airfoil profile

A wooden blade profile was cut to specification as shown in figure 2. Wood was used to make the master blade copy as shown in figure 3. Wood was chosen as it is cheaper and easier to make the glass fiber moulds shown in figure 4 [18]. The picture in figure 2 shows the NACA 0021 cut out airfoil profile. Figure 3 shows the master copy blade profile used to make the glass fibre mould. The final GFRP blade is shown in figure 5.

Fig. 2. Cut out NACA 0021 airfoil profile

Fig. 3. Cut out was used to align the wooden master copy

Fig. 4. The wooden blade master copy was used to make the GFRP mould

Fig. 5. Finished GFRP blade and the mould

4. Testing the Turbines

The VAWT was tested in a laboratory using a fan and later the turbine was tested in Ngong Hills under normal wind conditions. The wind turbine was connected to a generator produced by Akello *et al.* [19] and the performance was measured at different wind speeds.

In the laboratory the wind turbine was tested using a wind fan blowing laminar wind as shown in Figure 6. By varying the speed of the motor driving the wind fun using a variable drive the speed of the wind was also varied. This change in wind speed in turn caused a change in the rotation speed of the turbine.

Various speeds were used and the power output from the generator was measured using a power meter. Further, at the various set speeds, the static torque and rotational speeds were measured using a static torque meter and tachometer respectively.

For the field test the turbine was taken to Ngong Hills. This is an area known to have ample and reliable wind. The wind turbine was set up and the performance was measured from the generator using a power meter. The experiments were set up as shown in Figures 6 to 8.

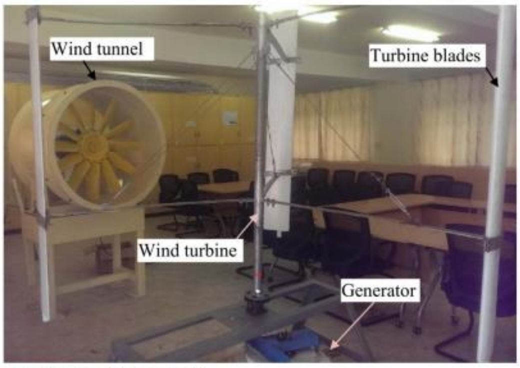


Fig. 6. Laboratory setup

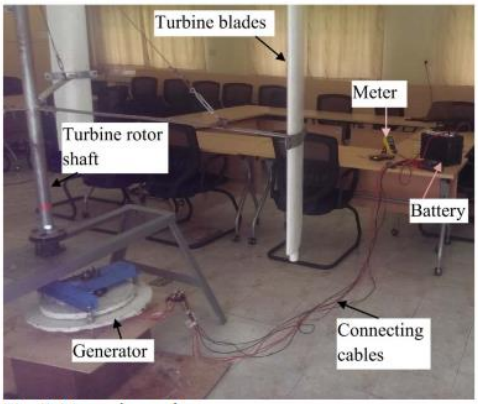


Fig. 7. Measuring gadgets

Fig. 8. Wind fan motor with a variable speed meter

Fig. 9. Field test at Ngong Hills

5. Results

Once the laboratory experiment was set up, the speed of the wind was changed by varying the rotational speed of the motor using the wind speed controller. The rotational speed of the wind turbine was simultaneously measured using the digital tachometers. It was observed that at a wind speed of 14 m/s the turbine gave the highest power of 190 W at 280 rpm, 12 m/s gave the highest power as 156 W at 230 rpm, 10 m/s gave the highest power as 120W at 180 rpm while 8 m/s gave the highest power as 96 W at 140 rpm. 250 is the rated RPM for the Generator. The turbine torque was 1.56Nm at an RPM of 175. These results are shown in figures 11 to 14

Figure 14 shows the curve for the rotational speed (rpm) of the turbine against the wind speed. This curve shows that the rotational speed of the turbine has a linear relationship with the prevailing wind speed. Figure 15 shows the torque versus the turbine rotational speed curve. This result is agrees with the equation 3 that guides the power output from a wind turbine.

Table 3: Power at different wind speeds and RPM

Wind speed (m/s)	Power (W)	RPM
6	50	118
8	96	140
10	120	180
12	156	230
14	190	280
16	170	290

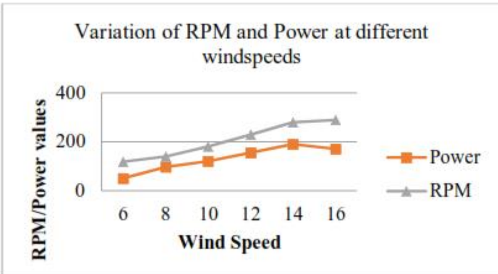


Fig. 10. Variation of RPM and power at different wind speeds

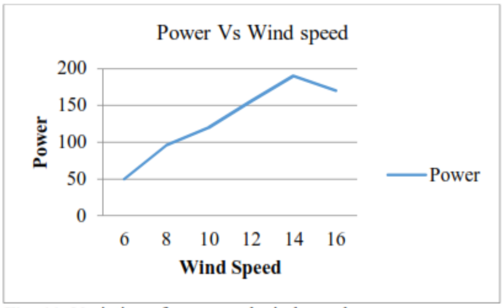


Fig. 11. Variation of power and wind speed

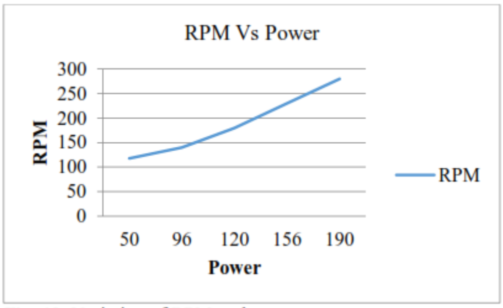


Fig. 12. Variation of RPM and power

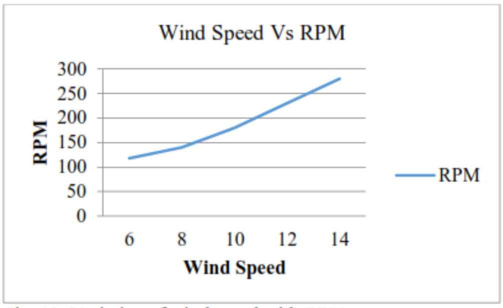


Fig. 13. Variation of wind speed with RPM

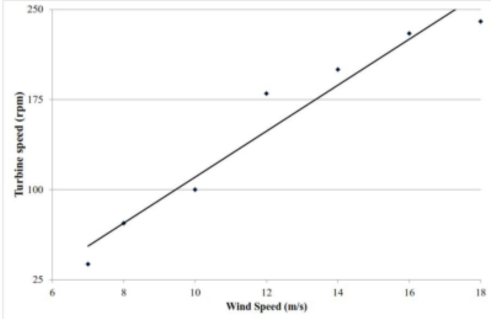


Fig. 14. Turbine speed versus wind speed

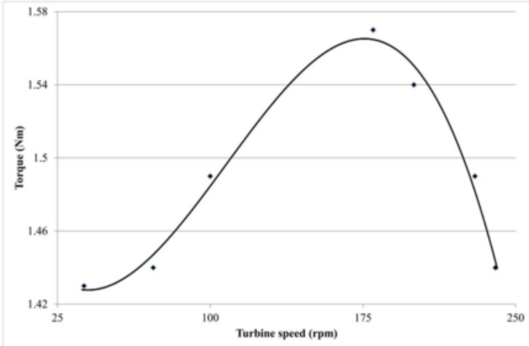


Fig. 15. Torque versus turbine speed

6. Costing Comparison

Technology mapping was conducted through consulting various industries. Players/promoters gave the various HAWT models that are sold/manufactured in Kenya Even though most of the local suppliers do not supply VAWT, the international price of VAWT of same sizing as developed in this study was found to be about US$ 1,000. This makes it more expensive when compared to the blade developed in this study.

The cost of production of the entire Rotor blade assembly was about KShs. 50,000. This cost included buying of the shaft, hubs and bearing (KShs. 25,000) and the blades amounted to about KShs. 21,000. A locally produced HAWT of the same sizing has a price range of KSH 100,000-200000.

7. Conclusions

A speed of 14 m/s gave the highest power of 190 W at 280 rpm, 12 m/s gave the highest power as 156 W at 230 rpm, 10 m/s gave the highest power as 120W at 180 rpm while 8 m/s gave the highest power as 96 W at 140 rpm. 2850 is the rated RPM for the Generator. The turbine torque was 1.56Nm at an RPM of 175. The turbine has high torque but low rotational speed. It is concluded that a high gear ratio generator may achieve higher power output. Alternatively, multi pole electrical generators can be used for direct coupling with the wind rotor... The cost of production of this studies Rotor blade with all components was about KShs. 50,000. This cost included buying of the shaft, hubs and bearing (KShs. 25,000) and the blades amounted to about KShs. 21,000. When compared to a HAWT turbine of same sizing it costs between 100000-200000. Most of the local suppliers do not supply VAWT, the international price of VAWT of same sizing as developed in this study is about US$ 1,000. In conclusion the blade produced in this study is cheaper when compared to locally produced HAWT and VAWT prices in international market. Power output can be enhanced with a multi-speed geared generator capable of stepping up the low rotational speeds of the turbine to high speeds.

Acknowledgement

The present work was supported by funds from the National Commission for Science, Technology and Innovation (NACOSTI) and the Bright Project under the wind turbine project.

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